NASA CR-121016
R72 AEG 296

PROPULSION SYSTEM STUDIES for an ADVANCED HIGH SUBSONIC, LONG RANGE JET COMMERCIAL TRANSPORT AIRCRAFT

by

(NASA-CR-121016) PROPULSION SYSTEM STUDIES FOR AN ADVANCED HIGH SUBSONIC, LONG RANGE JET COMMERCIAL TRANSPORT AIRCRAFT (General Electric Co.) Nov. 1972 152 p CSCL 21A
N73-11800
Unclas
G3/28 47341

GENERAL ELECTRIC COMPANY

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA-Lewis Research Center
Contract NAS 3-15544
Robert J. Antl, Project Manager

152

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-121016		

4. Title and Subtitle	5. Report Date
Propulsion System Studies for an Advanced High Subsonic, Long Range Jet Commercial Transport Aircraft	November, 1972
	6. Performing Organization Code
7. Author(s) General Electric Company	8. Performing Organization Report No. GE: R72 AEG 296
	10. Work Unit No.
9. Performing Organization Name and Address General Electric Company Aircraft Engine Group Cincinnati, Ohio 45215	11. Contract or Grant No. NAS3-15544
	13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

Propulsion system characteristics for a long range, high subsonic (Mach 0.90 - 0.98), jet commercial transport aircraft are studied to identify the most desirable cycle and engine configuration and to assess the payoff of advanced engine technologies applicable to the time frame of the late 1970's to the mid 1980's. An engine parametric study phase examines major cycle trends on the basis of aircraft economics. This is followed by the preliminary design of two advanced mixed exhaust turbofan engines pointed at two different technology levels (1970 and 1985 commercial certification for engines No. 1 and No. 2, respectively). The economic penalties of environmental constraints - noise and exhaust emissions - are assessed. The highest specific thrust engine (lowest bypass ratio for a given core technology) achievable with a single-stage fan yields the best economics for a Mach 0.95 - 0.98 aircraft and can meet the noise objectives specified, but with significant economic penalties. Advanced technologies which would allow high temperature and cycle pressure ratios to be used effectively are shown to provide significant improvement in mission performance which can partially offset the economic penalties incurred to meet lower noise goals. Advanced technology needs are identified; and, in particular, the initiation of an integrated fan and inlet aero/acoustic program is recommended.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Turbofan engines Subsonic aircraft Advanced technology Noise Emissions	Unclassified - limited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	151	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

This propulsion system study was performed for the National Aeronautics and Space Administration under Contract NAS3-15544 under the direction of the Lewis Research Center - Mr. J.H. Povolny, Program Manager and Mr. R.J. Antl, Project Engineer. The report was prepared by M.A. Compagnon, with contributions from A.J. Albright, R. Lee, and other General Electric personnel. W.R. Collier, the General Electric Program Manager, directed the overall study activity and R.E. Neitzel served as Technical Study Manager.

General Electric wishes to acknowledge the cooperation and support of the Advanced Transport Technology aircraft system contractors performing airplane studies (under contract to the Langley Research Center) in parallel with this propulsion system study, namely:

The Boeing Company - Seattle, Washington

General Dynamics Corporation - Fort Worth, Texas

Lockheed - Georgia Company - Marietta, Georgia

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SUMMARY

The overall objective of this study was to identify propulsion systems applicable to long range, high subsonic, jet commercial transport aircraft. Emphasis was placed upon advanced technology for engines designed for Mach 0.95 to 0.98 aircraft.

In the Task I parametric phase, the effects of variations in cycle and engine configuration on performance, weight, cost, installation, noise, emissions, and aircraft economics were examined. The significant results and conclusions reached in Task I are summarized below:

- For a Mach 0.98 aircraft, the highest specific thrust engine (lowest bypass ratio for given core technology) obtainable with a single-stage fan (assumed to be limited to 1.9 pressure ratio) yields the best mission performance.

- The above result applies for noise levels down to 15 EPNdB below FAR 36. Sideline jet noise becomes limiting for any lower level of engine noise.

- For a Mach 0.90 aircraft, the high specific thrust engine with a single-stage fan also yields good economics, but a somewhat lower specific thrust engine is also competitive.

- The single-stage-fan engine is lighter and less expensive than a two-stage fan in the specific thrust level where both could be considered. The two-stage fan is assessed as having a higher noise for a one-chord spacing based on limited experimental data. The single-stage approach therefore was recommended for Task II.

- A mixed exhaust configuration shows a significant advantage in mission performance over a separate exhaust configuration. In addition to the propulsive efficiency advantage, it allows a higher specific thrust cycle to be utilized within the pressure ratio limitation of a single-stage fan. The mixed flow approach was therefore recommended for Task II.

- Advanced core technology [1920° K (3000° F) turbine temperature and 35-40 cycle pressure ratio] can provide a significant improvement in mission performance based on projected cooling and materials development.

Based upon the results of the Task I study, two engines were selected for the Task II preliminary design effort. The distinguishing difference between the two engines was that of technology level. ATT No. 1 pointed toward the late-1970 time period. The primary objective of the design study was to provide sound engine data for the aircraft studies; study data on this

engine therefore were issued to the aircraft contractors. ATT No. 2 was pointed toward the mid-1980 time period, emphasizing advanced technology features for improved emissions, aircraft performance, and flight safety.

The primary characteristics of the engines designed for Task II are listed below and are illustrated in Figures 1 and 2.

Parameter	ATT No. 1	ATT No. 2
Timing	Late 1970's	Mid 1980's
Fan Pressure Ratio	1.83	1.85
Fan Tip Speed	503 m/sec (1650 ft/sec)	534 m/sec (1750 ft/sec)
Fan Type	Tip-shrouded titanium	Tip-shrouded "lightweight"
Bypass Ratio	4.1	5.6
Overall Pressure Ratio	30	37
Turbine Inlet Temperature (Takeoff)	1645° K (2500° F)	1920° K (3000° F)
Design Corrected Airflow	642 kg/sec (1415 lb/sec)	642 kg/sec (1415 lb/sec)
Rated Take-off Thrust	209 kN (47,000 lbs)	209 kN (47,000 lbs)
Cruise Thrust (M = 0.96, 37K)	53 kN (11,900 lbs)	53 kN (11,900 lbs)
Thrust/Weight	5.8 kg_f/kg (lb/lbm)	6.6-8.5 kg_f/kg (lb/lbm)
Exhaust Type	Mixed	Mixed

Note that a range of thrust/weight ratio is shown for ATT No. 2. The Lower level assumes mechanical design and materials technology similar to ATT No. 1, and the higher level assumes success on the very advanced features shown in the ATT No. 2 design. These features include the tip shrouded, lightweight (composite) fan blade, the fail safe design approaches to core turbine and fan discs, composite blading on the boosters and early stages of the core compressor, composite fan frame struts, laser-drilled film or film impingement turbine blades, and the use of advanced high temperature materials. Advances in component aerodynamics also have been incorporated into the ATT No. 2 design. A comparison of the ATT No. 2 engine with a current engine, the CF6-50, is shown in Figure 3. The engines are scaled to the same take-off thrust, but the ATT engine would have considerably higher thrust at the ATT cruise point.

In order to achieve a noise level of 10 EPNdB below FAR 36 for ATT No. 1, a single inlet splitter and extensive wall suppression are required. Fan noise is the major noise contributor with the estimates based on the extrapolation of the results of Fan C tests in the NASA-GE Quiet Engine Program.

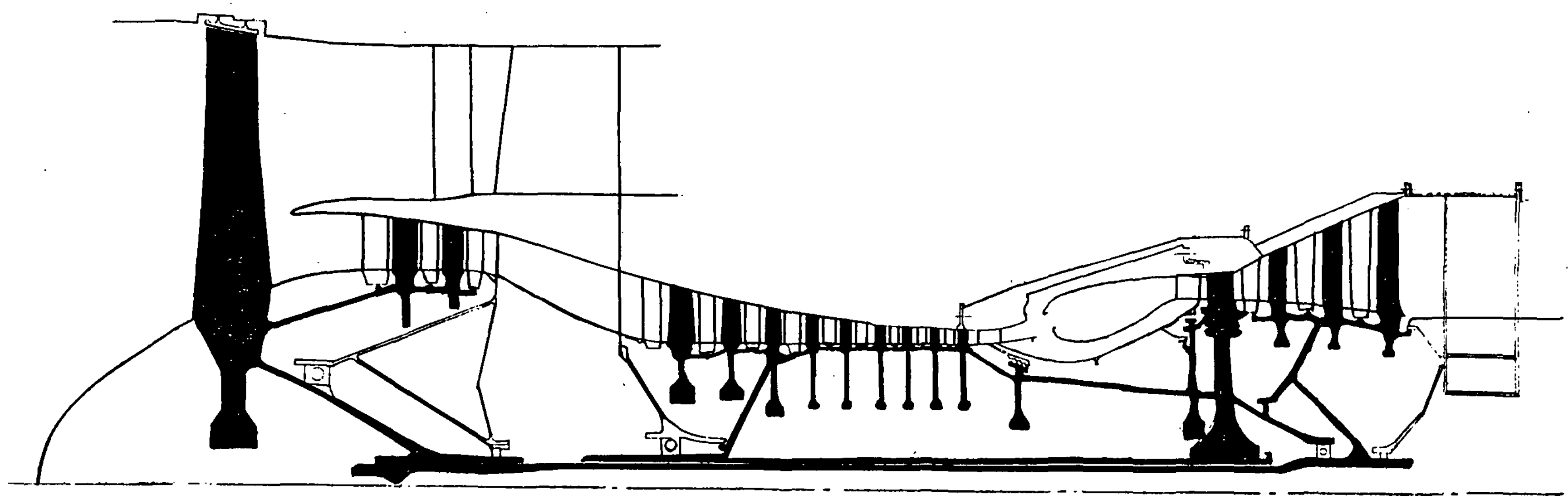


Figure 1. ATT No. 1 Bare Engine Cross Section Schematic.

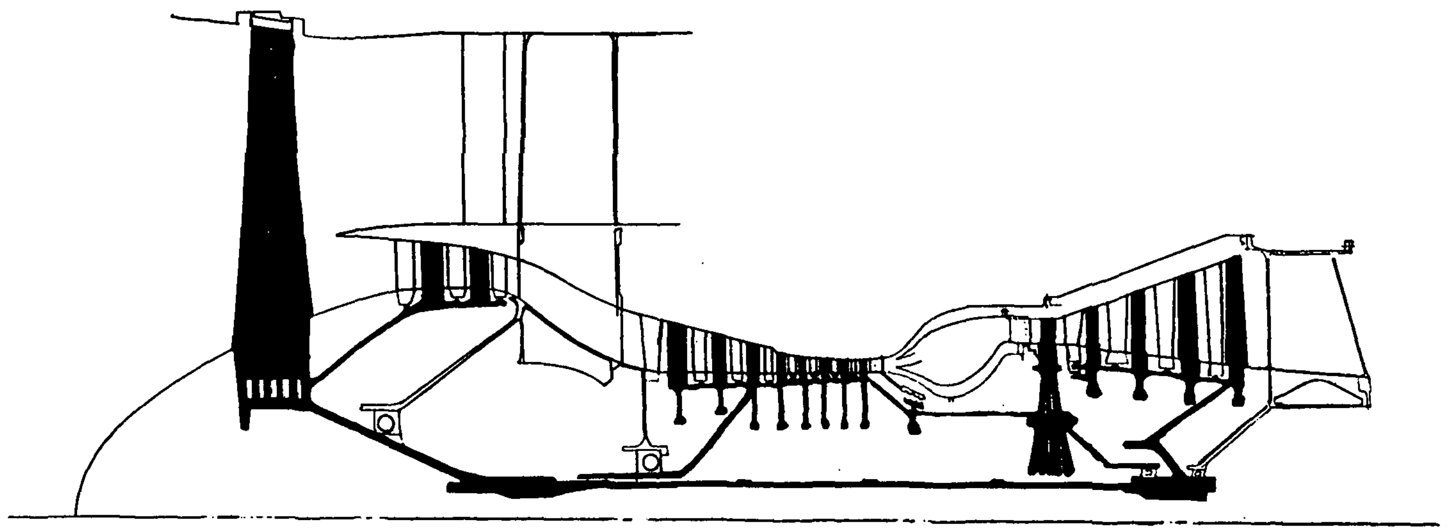


Figure 2. ATT No. 2 Bare Engine Cross Section Schematic.

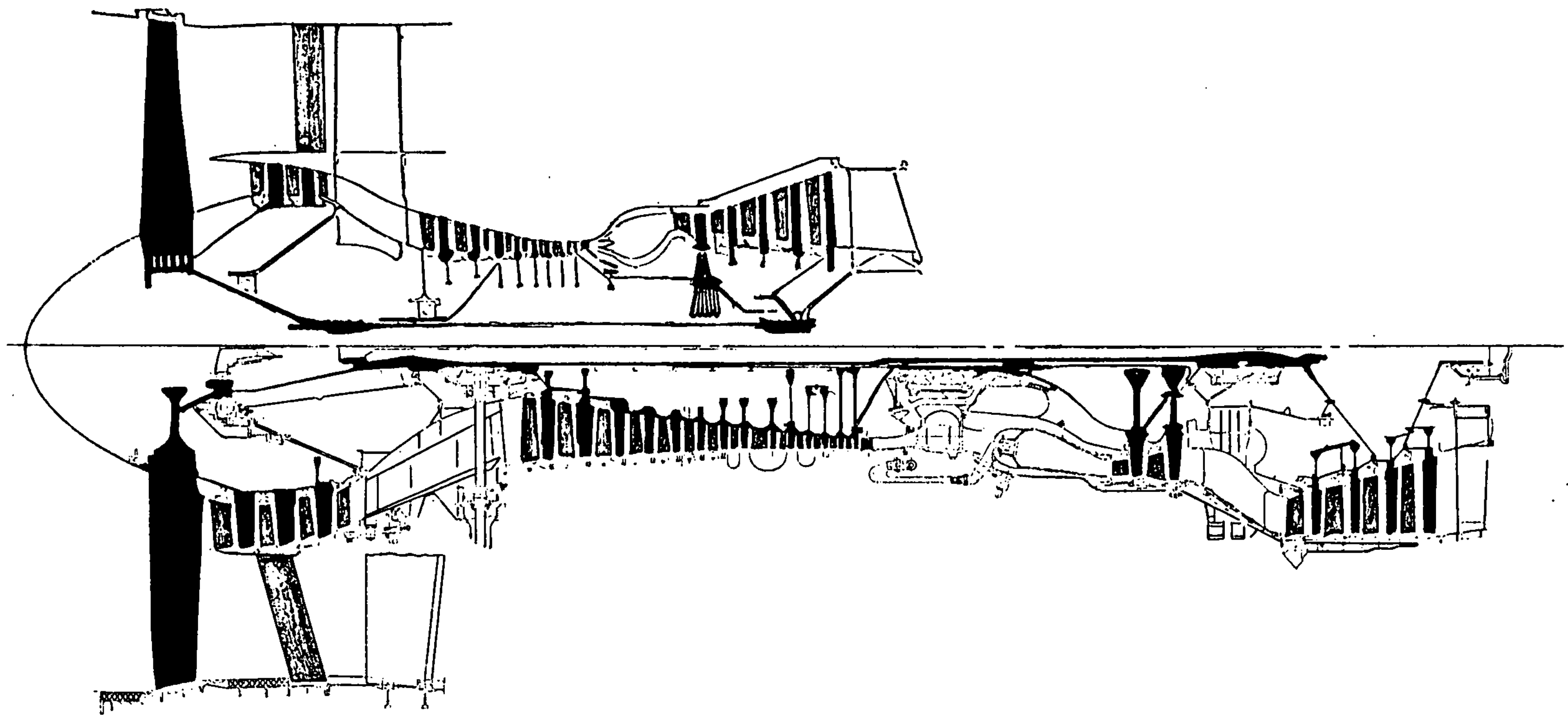


Figure 3. ATT No. 2/CF6-50 Engine Comparison.

For ATT No. 2, it was necessary to use two inlet and two aft splitters in addition to assuming an improvement in fan noise technology to achieve the study objective of 15 EPNdB below FAR 36 (without novel flight procedures).

Economic penalties of splitters are quite large. It is recommended that the objective for such an engine should be to achieve a noise level of 10 EPNdB below FAR 36 with minimum economic penalty, specifically by reducing fan noise such that wall suppression only is required.

The idle emissions objectives can be achieved by means of specific features designed into the engine. For ATT No. 1, a bleed port with 15% core bleed capacity is incorporated into the combustor so that the fuel/air ratio required to achieve idle thrust can be increased to a value where the combustor efficiency is improved and emissions reduced. For ATT No. 2, a double-annular combustor is shown. The inner bank would be shut off at idle, yielding emissions lower than the contract objective.

The NO_x emissions objectives of this contract cannot be met without the use of water injection, although the advanced carbureting combustors are projected to provide an improvement over current technology combustors. The use of water only at takeoff for NO_x emissions reduction will result in a relatively small penalty to aircraft gross weight. An order-of-magnitude-greater penalty would be involved in reducing cycle pressure ratio and turbine inlet temperature to achieve a lesser reduction in NO_x emissions.

Improvements in engine technology to balance the economic penalties of lower noise can be quite attractive. The ATT No. 1 engine is estimated to offer an improvement in DOC on the order of 5% for a Mach 0.98 mission over an engine based on current technology. It should be noted that a significant portion of this improvement is associated with the use of the higher-fan-pressure-ratio, mixed-flow cycle (higher specific thrust) which is tailored to the ATT mission. The ATT No. 2 engine is estimated to offer an improvement in DOC of 3% to 5%, depending upon weight level, over the ATT No. 1 engine. Since the propulsive cycles are similar, this is purely due to technology improvements which will require extensive development effort over a period of time.

The major program recommendation (Task III) is to initiate an integrated fan and inlet aeroacoustic program with the objective of achieving a low-noise, single-stage fan with a pressure ratio of approximately 1.85 with efficiency, specific flow, and stall margin suitable for the Mach 0.95 to 0.98 application. This program should include inlet features (fixed and variable) to reduce inlet transmitted noise, particularly the multiple pure tones associated with high blade Mach numbers. There is little background on high-pressure-ratio, single-stage fans designed for low noise (Fan C of the NASA-GE Quiet Engine Program is closest in terms of tip speed) and a suitable program on this key element of the near sonic engine clearly is indicated.

In addition to fan aerodynamics and noise, other areas are of importance to the ATT-type engine. Installation aerodynamics associated with Mach 0.95 - 0.98 flight will require experimental work. The mixed exhaust system is shown to have high payoff for the ATT application and deserves attention. The tip

shrouded lightweight fan blade will require considerable design and development effort, as will composites in general, and this effort should be pursued. Emissions features and general noise technology work are important and are expected to be pursued under other programs. It is proposed that improved flight safety also be a focal point of advanced technology work, the disc-burst problem being the most important. Follow-on design studies should be conducted to identify further the payoff of alternate engine features and to guide the component research work associated with this type of engine and application.

Since General Electric does not believe that a new long range higher Mach aircraft will be developed for the late 1970's, it is recommended that NASA point toward advanced engine technology for the 1980's with the objective of improving aircraft economics and speed, thereby providing the necessary incentive for new aircraft development.

INTRODUCTION

NASA is studying the application of advanced technologies to long range, high subsonic, jet commercial transport aircraft. To assure that future transport aircraft will be responsive to national needs and that the required technology will be ready for application in the late 1970 to the mid-1980 time period, the benefits of technology advances in aerodynamics, propulsion, structures, control, and avionics are being assessed.

This study, sponsored by NASA under the direction of the Lewis Research Center, is concerned with the propulsion system. Its objectives are to identify the most desirable cycle and engine configuration applicable to an aircraft in the speed range of Mach 0.90 to 0.98, and to assess the payoff of advanced engine technologies consistent with the above time frame. In the category of advanced technologies, control of the environmental factors of noise and pollution figures prominantly, and considerable effort is given to make the propulsion system quiet and clean. The above objectives, therefore, are to be realized within certain environmental constraints specified by NASA for noise and exhaust emissions.

The material presented in this report is organized in three tasks:

- Task I is an engine parametric study designed to explore major cycle trends and the effect of cycle variations on noise and exhaust emissions. The economic penalties of meeting specific noise constraints are assessed.

- The results of the parametric engine evaluation form the basis for the selection of two cases which are then carried through an engine preliminary design evaluation in Task II.

- Advanced engine technology needs are identified in Task III and specific technology programs are recommended.

During the course of the study, close coordination was maintained with those airframe contractors who were conducting advanced technology airplane system studies, under the direction of the Langley Research Center, in parallel with the engine studies. Preliminary engine data were provided for these contractors to exercise their parametric study airplanes at the beginning of Task I; and, more specific data reflecting the characteristics of a cycle selected at the conclusion of Task I were issued at the onset of Task II. This close coordination resulted in a valuable interchange of information relative to installation aspects in particular. It also ensured the definition of reasonable airplanes and procedures to develop suitable engine economic trade factors by using these airplanes as host airplanes to evaluate the family of parametric engines.

TASK I - TURBOFAN ENGINE PARAMETRIC STUDY

GENERAL APPROACH

The overall approach used in Task II to screen cycles and to arrive at the two cycles selected for preliminary engine design is shown in Table I. From a large parametric cycle design point study covering the wide range of parameters shown in Table II, approximately 60 cases were selected to cover the range of basic parameters of interest. These cases were carried through a systematic evaluation involving:

- Component definition and sizing
- Engine flowpath definition
- Installation aerodynamic definition
- Basic engine and installation weight estimates
- Basic engine and installation cost estimates
- Noise estimates
- Pertinent emission trends

Mission sensitivity or trade factors for the Mach 0.90 and 0.98 host airplanes were developed. These factors then were used to evaluate the families of parametric engines on the basis of relative aircraft gross weight and economics (ΔDOC and ΔROI), with and without noise constraints.

Scope of Specific Study

The major parameters evaluated are listed in the left hand column of Table III. These parameters were exercised over the range indicated and evaluated relative to the base cycle shown in the right hand column for selected values of the other parameters.

Note that, throughout the parametric study, specific thrust (Fn/W_2) is used as a major variable because it is more fundamental than bypass ratio for the following reasons:

- A given specific thrust reflects a constant propulsive efficiency at a given flight speed; and, therefore, the separate cycle effects which define thermal efficiency can be observed independently and vice versa.
- Thrust lapse rate is very nearly defined by specific thrust (for a given ΔT_4).

TABLE I. PARAMETRIC ENGINE SCREENING STUDY FLOWCHART.

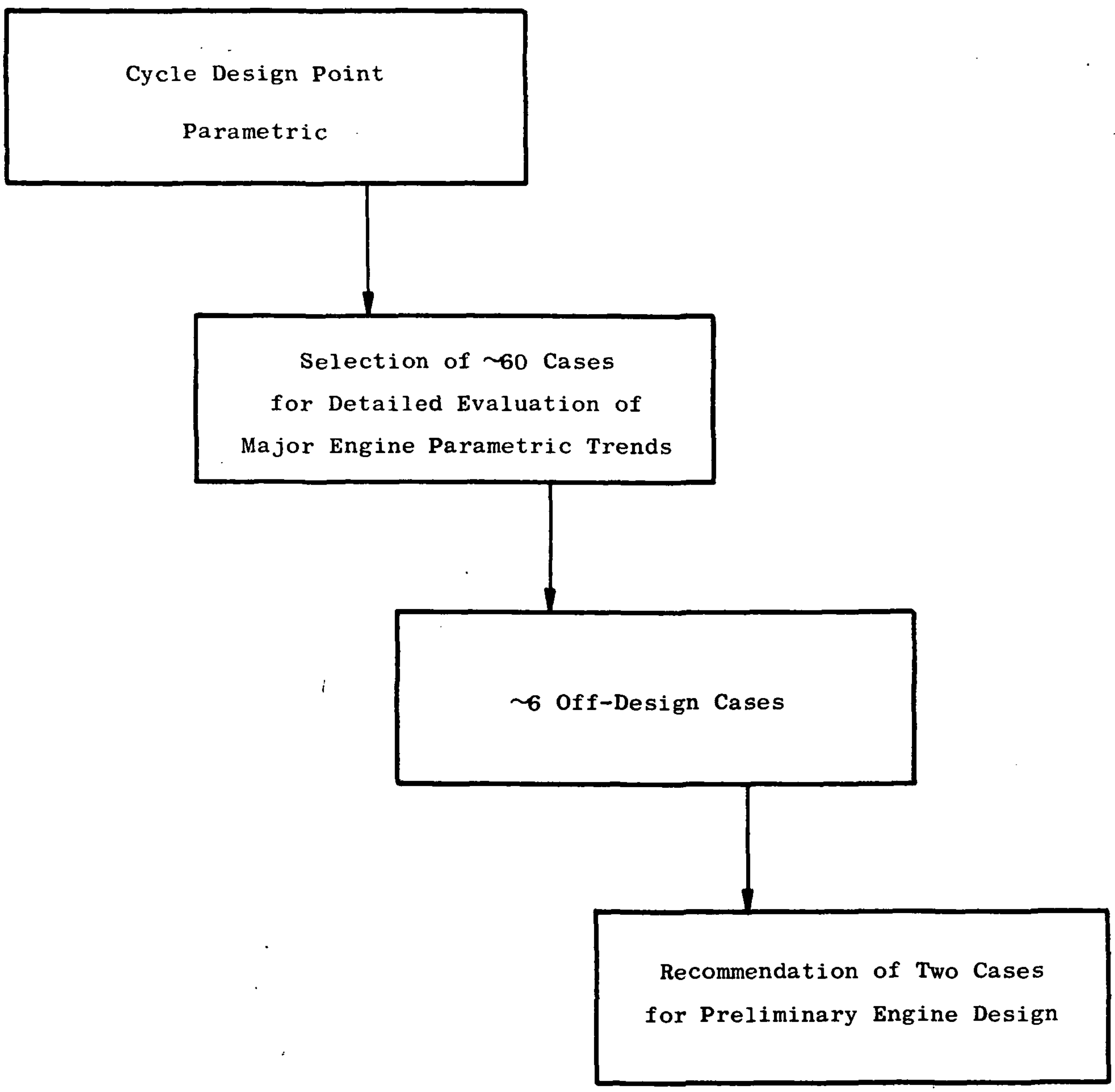


TABLE II. INITIAL CYCLE DESIGN POINT PARAMETRIC STUDY GRID.

- FLIGHT CONDITION
  - 12,192 m (40,000 ft)
  - Mach Number = 0.96
  - Standard + 10° C Day

- MATRIX

F_N/W_2, kgf/kg/sec (lb/lbm/sec)	12 to 37	
P_3/P_2	15 to 40	
T_4, Maximum Cruise, Standard + 10° C Day	1250 to 1860 K (1790° to 2890° F)	150 Cycles
Takeoff, Standard + 14° C Day (84° F) Day	1310 to 1920 K (1900° to 3000° F)	x → 300 Cycles

- CONFIGURATIONS

Mixed Exhaust, Long Cowl	2
Separate Exhaust, $\frac{3}{4}$ Cowl	x

- INSTALLATION VARIATIONS

2 → 600 Cycles

With and Without Installation Effects

- Interstage Bleed, 0.9072 kg/sec/engine (2.0 lbs/sec/engine) (44,482 N Cruise Thrust) (10,000 lbs)
- Extraction, 74.6 kilowatt (100 hp)
- Ram Recovery, 0.9975

With and Without Nacelle Drag

- Drag = $f(W\sqrt{\theta}/\delta)$

TABLE III. ENGINE PARAMETRIC STUDY GRID.

Parameters Varied	Range	Base Cycle
F_N/W_2, Specific Thrust at Cruise, Standard + 10° C Day	12 to 30 kgf/kg/sec (lb/lbm/sec)	19
T_4, Turbine Inlet Temperature, Standard + 14° C Day (84° F Day) at Takeoff	1310 to 1920 K (1900° to 3000° F)	1590 K (2400° F)
P_3/P_2, Cycle Pressure Ratio at Cruise	15 to 40	30
Exhaust System	Mixed and Separate	Mixed
V_9/V_{29}, Primary/Fan Jet Velocity (Energy Extraction§)	1.1 to 1.5§	1.3§
Flight Mach Number	0.90 to 0.98	---
Acoustic Treatment	Wall, Wall and Splitters	Wall Only
Water Injection (NO_x Control)	With and Without	Without

§ Applies to Separate Flow Cycle only.

- Specific thrust defines an average jet velocity and is, therefore, the primary cycle parameter associated with jet noise.

- For a given exhaust configuration (mixed or separate) and a consistent energy extraction level, specific thrust defines fan pressure ratio within a narrow range.

Finally, and perhaps most importantly,

- For a family of fans (constant radius ratio and specific flow), specific thrust establishes fan size for a given thrust level and, to a first approximation, pod size and installation drag.

Specific thrust, therefore, is the primary variable exercised for both mixed and separate exhaust engine configurations to identify the fan size (and bypass ratio for a given core technology) which yields the best airplane economics, both with and without noise constraints.

Logical combinations of turbine inlet temperature and cycle pressure ratio were evaluated at a specific thrust of 19 (constant propulsive efficiency systems) to show the payoff of technology associated with high thermal efficiency cycles (high T_4 and cycle pressure ratio).

Mixed and separate exhaust configurations were evaluated over the full range of specific thrust for two combinations of turbine inlet temperature and cycle pressure ratio representing two levels of core technology as follows:

Turbine Inlet Temperature (T_4) Takeoff - std + 14° C (+25° F)	Cycle Pressure Ratio (P_3/P_2)
1) 1590° K (2400° F)	30
2) 1950° K (3000° F)	40

For the separate exhaust cycles, energy extraction, which describes the split in energy between the bypass and core streams, was varied over the range of jet exhaust velocity ratios shown in Table III to determine the optimum extraction from a mission standpoint without noise constraints. The base value of jet velocity ratio of 1.3 was selected as a good compromise between mission performance and jet noise.

The effect of a cruise Mach number lower than 0.98 on the choice of specific thrust was evaluated, but the bulk of the study emphasizes the higher cruise Mach number range.

Finally, the economic penalties of increasing acoustic treatment from that of the base case to achieve lower noise, and the effect of water injection on the emissions of nitrogen oxides were estimated.

CYCLE STUDIES

Cruise Design Point (Maximum Cruise Rating) and Cycle Match

The cycle match point for all the parametric cases was chosen at a representative cruise flight condition for the Advanced Transport Technology (ATT) airplane, namely Mach 0.96 at 12,200 meters (40,000 feet). Simple corrections to adjust sfc and thrust to other Mach numbers (0.90 and 0.98) were developed and applied as required. Components were matched to operate at their respective aerodynamic design point, and the cycles were defined for a reasonable energy extraction level which was set as follows:

Configuration	Energy Extraction Defined by
1) Separate Exhaust	$\frac{\text{Core exhaust jet velocity}}{\text{Fan exhaust jet velocity}} = 1.3$
2) Mixed Exhaust	Equal total pressure in the plane of mixing for near optimum energy extraction

All engines were sized and matched with representative installation losses for a commercial aircraft as follows:

- 0.9 kg/sec (2 lb/sec) interstage bleed air
- 74.6 kilowatt (100 hp) extraction
- Cruise ram recovery of 0.994.

Engine Ratings

Engine ratings were established for the parametric engines on the basis that the aircraft cruise thrust, rather than take-off thrust, would size the engines because of the high cruising altitude of the ATT airplane. Accordingly, the following turbine inlet temperature ratings were selected for all engines at their flat rated ambient temperature conditions:

T_4 cruise = T_4 at takeoff - 56° C (-110° F)

T_4 climb = T_4 at takeoff - 17° C (-30° F)

Takeoff was flat rated to a standard +14° C (+25° F) day. Maximum cruise and maximum climb were flat rated to a standard +10° C (+18° F) day.

Temperatures shown on the various illustrations are always hot day temperatures as defined above.

Engine Study Size

The parametric engine study was conducted in a thrust size of 44.48 kN (10,000 lbs) at the cruise design point defined above. This corresponds to a sea level static take-off thrust varying approximately between 178 and 205 kN (40,000 and 46,000 lbs), depending on the specific thrust at cruise and the installation losses at takeoff (primarily ram recovery). The engines then were scaled for the mission evaluation to accommodate the thrust size of the host airplanes described later.

Component and Cycle Assumptions

As is generally the procedure for parametric cycle data, representative values of component efficiencies (usually polytropic) were used and held constant, along with other cycle losses (ΔP's). In this study, performance refinements were made to account for the important fan component design variations and the fan exhaust duct mixer pressure losses as discussed below.

To cover the range of fan pressure ratios required (1.5 to 3.2) in this parametric study, both single- and two-stage fans were required. A maximum fan pressure ratio of 1.9 was established as a reasonable limit for advanced single-stage fan designs with a maximum corrected tip speed of 550 m/sec (1800 ft/sec). The schedules of fan pressure ratio and fan efficiency versus fan tip speed which were established are shown in Figures 4 and 5 for single- and two-stage designs, respectively. It should be noted that the two-stage fans have higher efficiencies (2 - 3%) in the range of pressure ratios where both single- and two-stage fans logically can be considered.

Duct and mixer losses are dependent on the specific geometry of each engine. Simple estimates of pressure losses were made as a function of bypass ratio to reflect these geometry variations from engine to engine. The fan duct pressure losses shown in Figure 6 include estimates of wall sound suppression treatment losses.

DEFINITION OF PARAMETRIC ENGINES

Air Design and Component Sizing

A layout of an advanced dual-rotor turbofan engine similar to that shown in Figure 1 was used as a model to establish consistent parametric component sizing and flowpath layout procedures. A low-aspect-ratio, unshrouded fan of composite construction was used as a model for the single-stage fan. A high-aspect-ratio, tip shrouded design of titanium construction was assessed as having less penalty for the two-stage fan configurations than a wide chord design of composite construction. For noise reasons, a one-chord spacing between blade rows was used for the two-stage fan and the length increase with a wide chord design would have entailed a significant increase in engine length and installation weight. A detailed component sizing and flowpath design procedure was developed on simple but consistent ground rules.

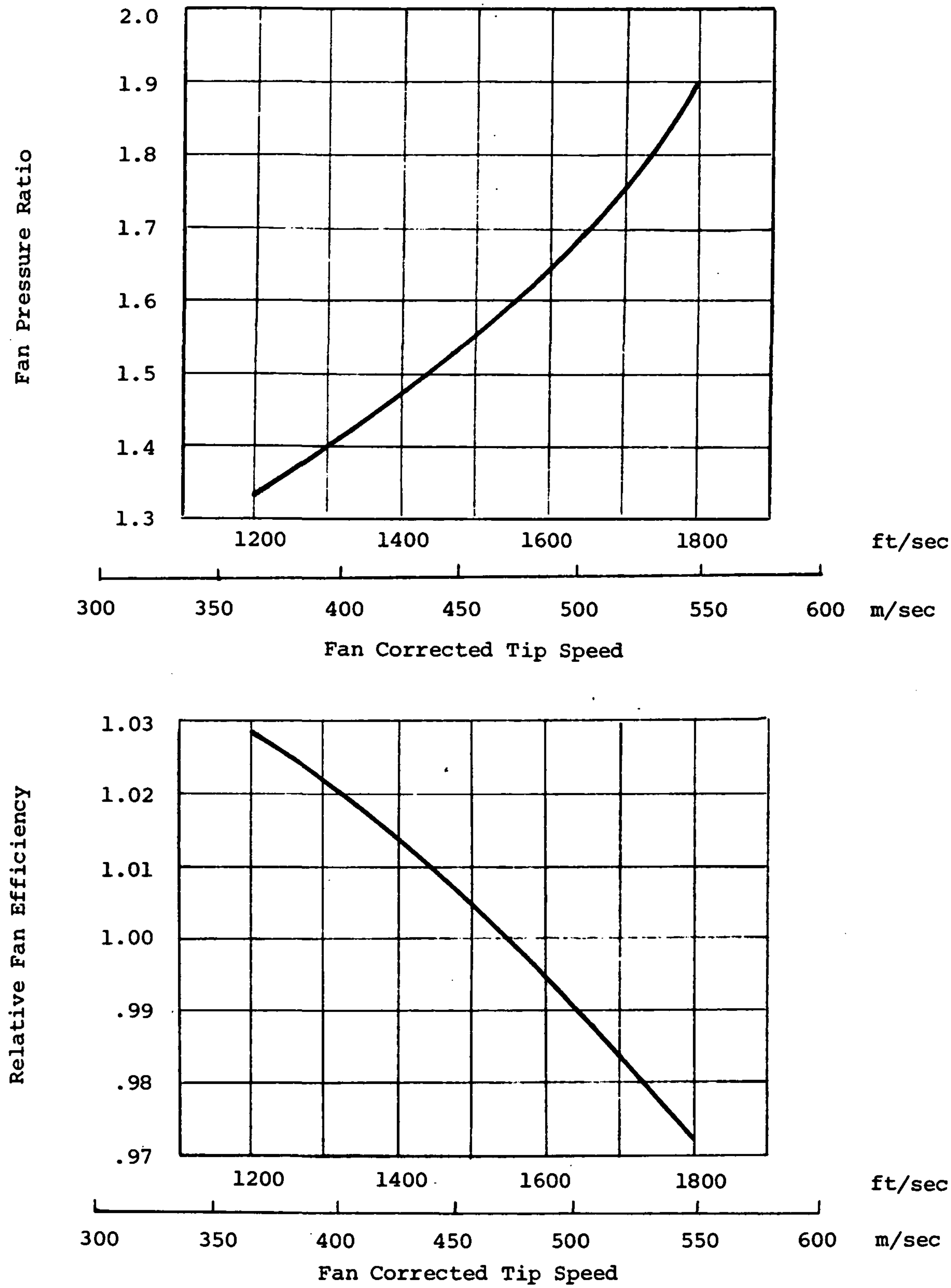


Figure 4. Single-Stage Fan Design Point Performance Characteristics.

ENGINE PARAMETRIC STUDY

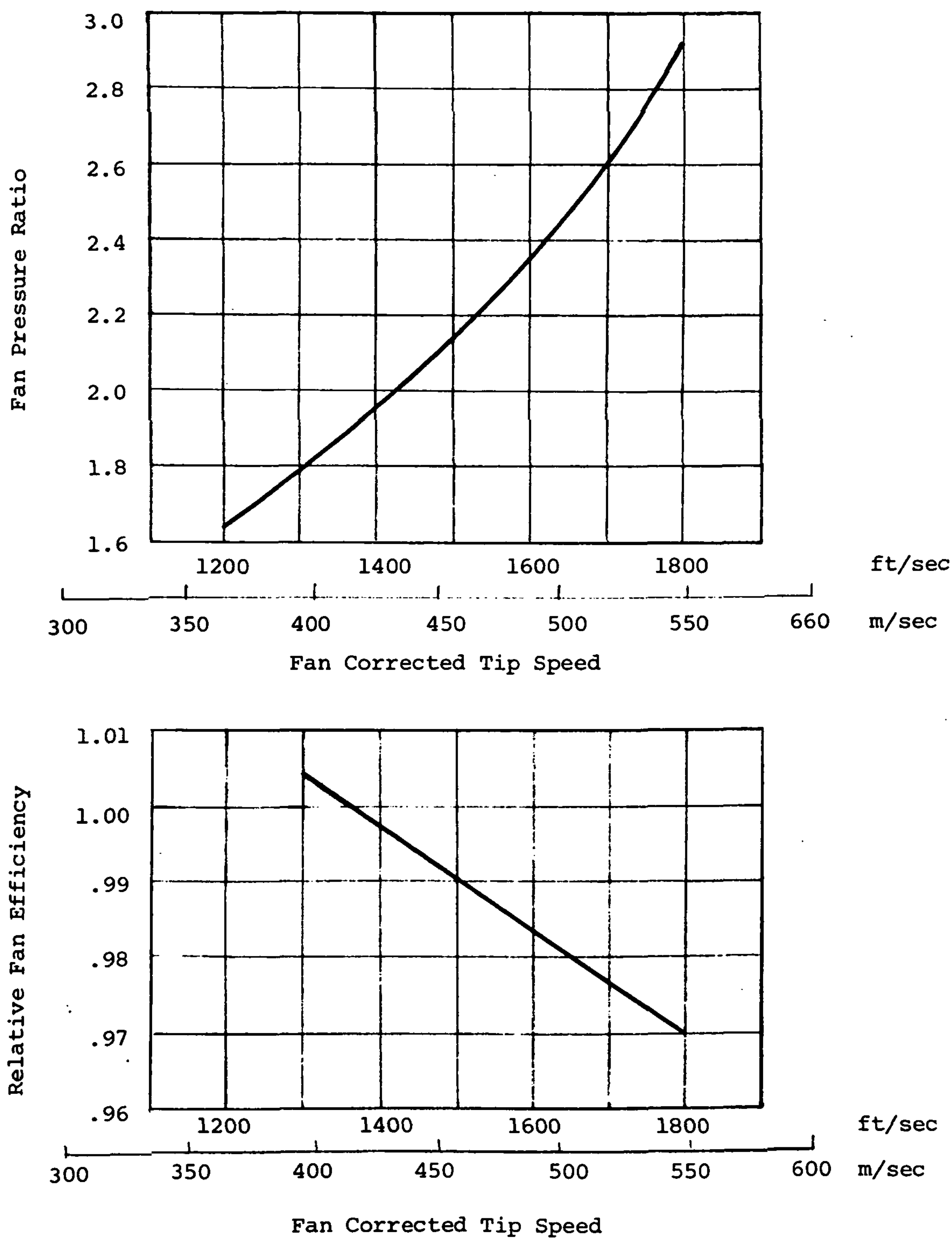
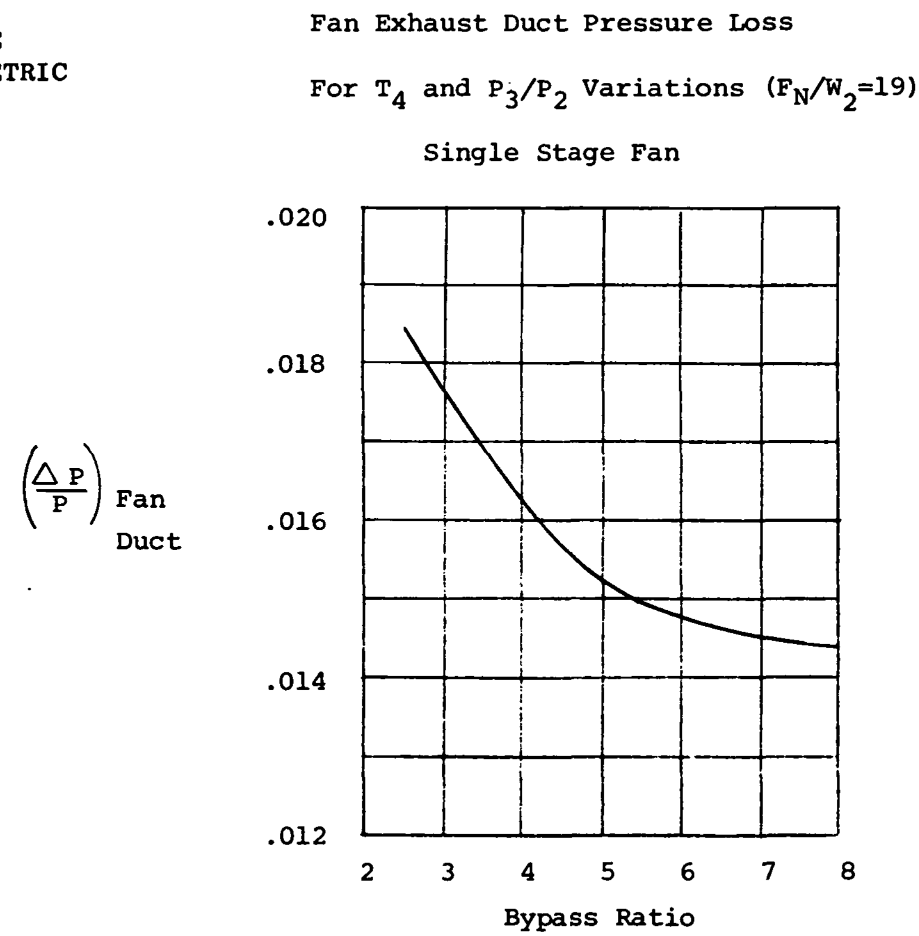


Figure 5. Two-Stage Fan Design Point Performance Characteristics.



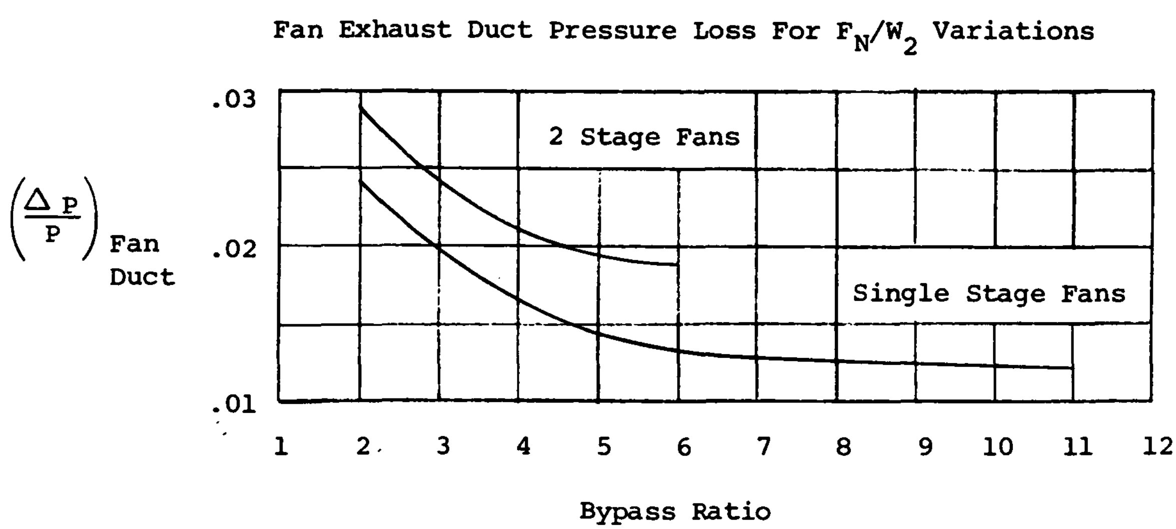


Figure 6. Variation of System Pressure Losses.

The outputs of the component sizing program then were used as inputs for the nacelle layouts and weight estimates. Simple engine schematics were made to ensure that reasonable flowpaths were indeed obtained.

Installation

A simple but consistent approach was evolved to define systematically a representative family of nacelles for high subsonic applications. These ground rules were established after consultation with the ATT airframe contractors. The nacelles were configured to have relatively high fineness ratios and low curvature and boattail angles for the high-Mach-number application involved.

Two cruise Mach numbers were specifically considered; i.e., Mach 0.90 and 0.98. A variable geometry inlet lip was assumed for a cruise Mach number of 0.98, whereas a fixed geometry inlet was considered reasonable for the lower cruise Mach number of 0.90.

The general aerodynamic guidelines used for the inlet, nacelle, and afterbody are shown in Table IV for the mixed exhaust engine configurations and in Table V for the separate exhaust parametric engines.

Nacelle structural guidelines also were established as shown in Table VI to provide consistent clearances, mounting arrangement, and allowances for fan and core reversers. A minimum reverse thrust of 30% of total forward thrust was used as the basis for establishing where a full reverser for the mixed exhaust configuration was needed or, for the separate exhaust cases, where a fan reverser plus a core spoiler were required, rather than a fan reverser alone. This requirement defined the approximate bypass ratios (shown in Table VI) where the transition was made for each configuration. Figure 7 illustrates schematically the effect of specific thrust on mixed- and separate-flow nacelle size for a constant installed cruise thrust.

A standard procedure for estimating isolated nacelle drag in the current subsonic Mach number range was adopted for the ATT nacelles. A supervelocity effect on cowl friction drag was included. The drag elements for mixed and separate exhaust configurations are shown in Figure 8 together with values for a representative parametric case. Drag variations as a function of engine specific thrust are shown for mixed and separate exhaust cases in Figure 9. Drag levels are slightly higher for two-stage fan configurations because of the longer cowl and the higher cowl diameter resulting from the higher fan radius ratio. Drag differences between mixed and separate exhaust configurations are relatively small over the complete range of specific thrusts investigated.

It is recognized that interference effects will pay a larger part in the nacelle design and engine location for the near sonic flight regime of this application. At the present time, little information regarding these effects is available to provide sound design guidelines, other than to maintain high fineness ratio nacelles. Therefore, the interference effects will eventually have to be determined from wind tunnel tests for specific engine/airplane configurations.

TABLE IV. NACELLE AERODYNAMIC GUIDELINES, MIXED FLOW CYCLE.

Engine Parametric Study

Cruise Mach Number	0.98	0.90
• **INLET** Inlet Geometry	Variable Geometry Lip Pressure Actuated Minimum Fan Face Distortion	Fixed Geometry, Thinner and Longer Version of DC-10
Maximum Throat Mach Number, at Maximum Power Climb	0.75	0.75
Internal Contraction	$D_{HL}/D_{throat} = 1.08$	$D_{HL}/D_{throat} = 1.12$
External Lip	$D_{HL}/D_{maximum} = 0.88$	$D_{HL}/D_{maximum} = 0.85$
Length	$L/D_{maximum} = 1.3$	$L/D_{maximum} = 0.8$
• **NACELLE AND AFTERBODY** Maximum Local Boattail Angle	0.140 to 0.175 rad (8° to 10°)	0.175 to 0.209 rad (10° to 12°)
Aft Cowl Length	Set by Mixing Length	Set by Mixing Length
Plug Type Nozzle Chordal Plug Angle	0.209 rad (12°)	0.209 rad (12°)
Plug Diameter Choice Influenced by:	• Constraint on Maximum Area Ratio • Constraint on Minimum Area Ratio • Chordal Upstream Wall Angle = 0.262 rad (15°)	• Constraint on Maximum Area Ratio • Constraint on Minimum Area Ratio • Chordal Upstream Wall Angle = 0.262 rad (15°)
Minimum Reverse Thrust	30% of Take-off F_N	30% of Take-off F_N

TABLE V. NACELLE AERODYNAMIC GUIDELINES, SEPARATE FLOW CYCLE.

Engine Parametric Study

Cruise Mach Number	0.98	0.90
• INLET	Same as MIXED FLOW	Same as MIXED FLOW
• NACELLE AND AFTERBODY		
Maximum Fan Cowl Local Boat-tail Angle	0.122 to 0.157 rad (7° to 9°)	0.140 to 0.175 rad (8° to 10°)
Fan Cowl Length	Extends to Aft Turbine Frame	Extends to Aft Turbine Frame
Waist Cowl Diameter	Set by Turbine Diameter	Set by Turbine Diameter
Chordal Waist Cowl Angle	0.209 rad (12°)	0.209 rad (12°)
Plug Type Nozzle, Chordal Plug Angle	0.209 rad (12°)	0.209 rad (12°)
Constraints on Fan and Core Nozzle Area Ratio	Same as MIXED FLOW	Same as MIXED FLOW
Minimum Reverse Thrust	30% of Take-off F_N	30% of Take-off F_N

TABLE VI. NACELLE STRUCTURAL GUIDELINES, MIXED AND SEPARATE EXHAUST.

Engine Parametric Study

Both M = 0.98 and 0.90

- MIXED AND SEPARATE FLOW NACELLES
  - Minimum Cowl Thickness over Fan Tip $\approx$ 10 cm (4 in.)
  - Frame Permits Top or Side Mounting
  - Cascade Type Fan Thrust Reverser (CF6-6 Type)
  - Minimum Thickness over Turbine Flange $\approx$ 2-1/2 cm (1 in.)

- MIXED FLOW NACELLES
  - Minimum Cowl Thickness over Mixer $\approx$ 5 cm (2 in.)
  - Fan and Core Thrust Reverser for $\beta \leqq 5$

- SEPARATE FLOW NACELLES
  - Core Exhaust Reverser/Spoiler (CF6-50 Type) for $\beta \leqq 8.5$

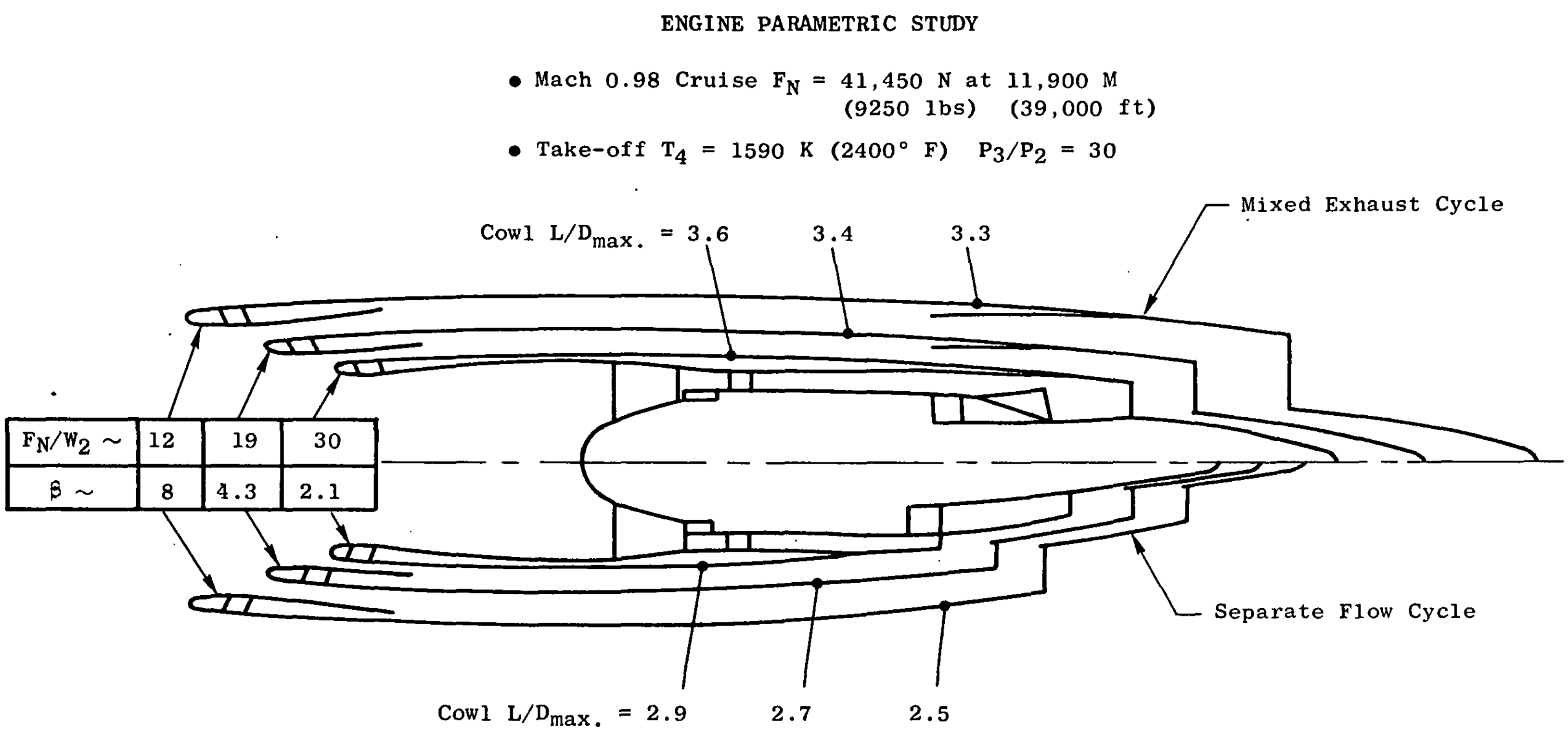


Figure 7. Influence of Specific Thrust on Nacelle Size.

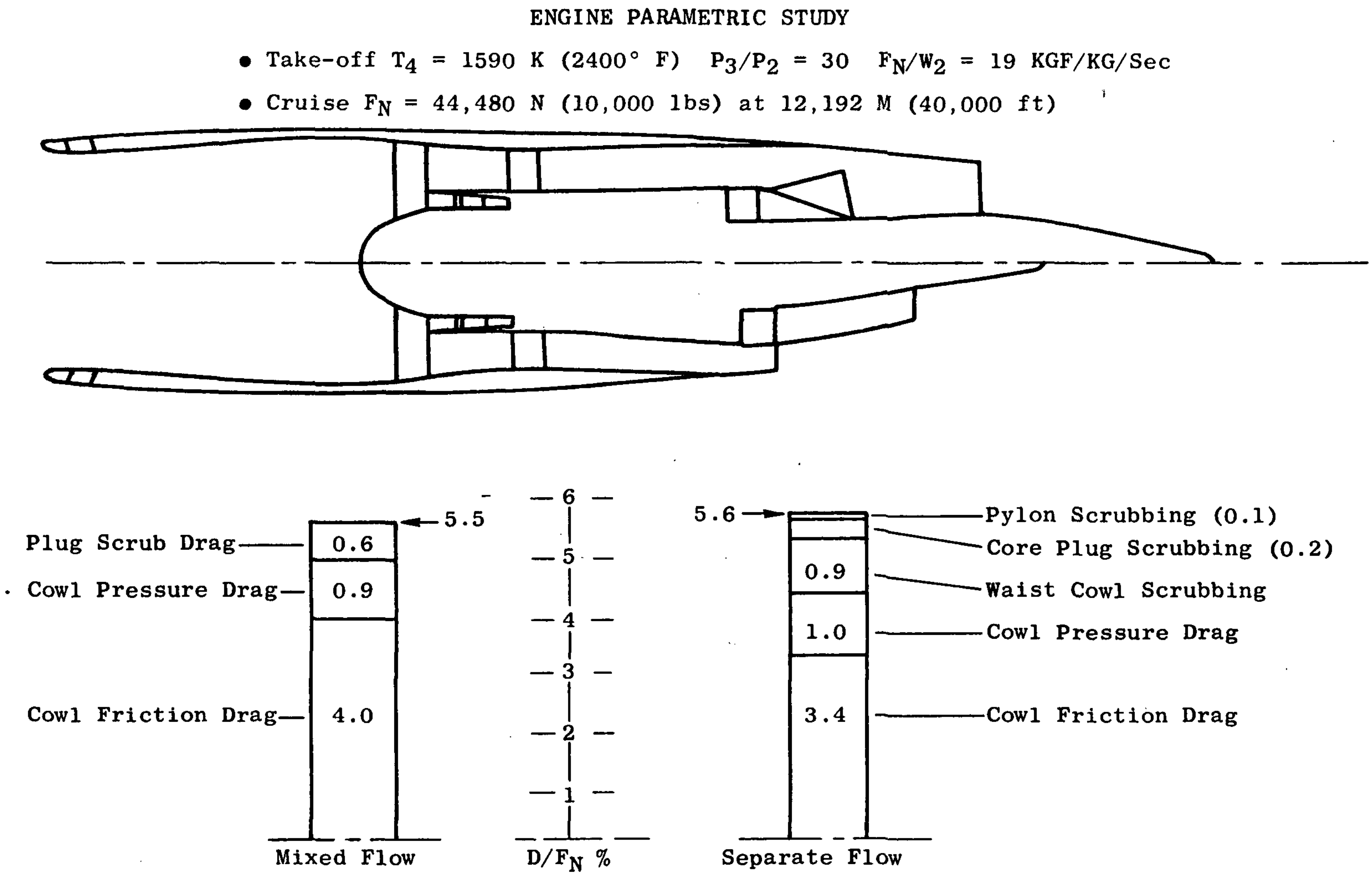


Figure 8. Mach 0.98 Cruise Installation Drag Breakdown.

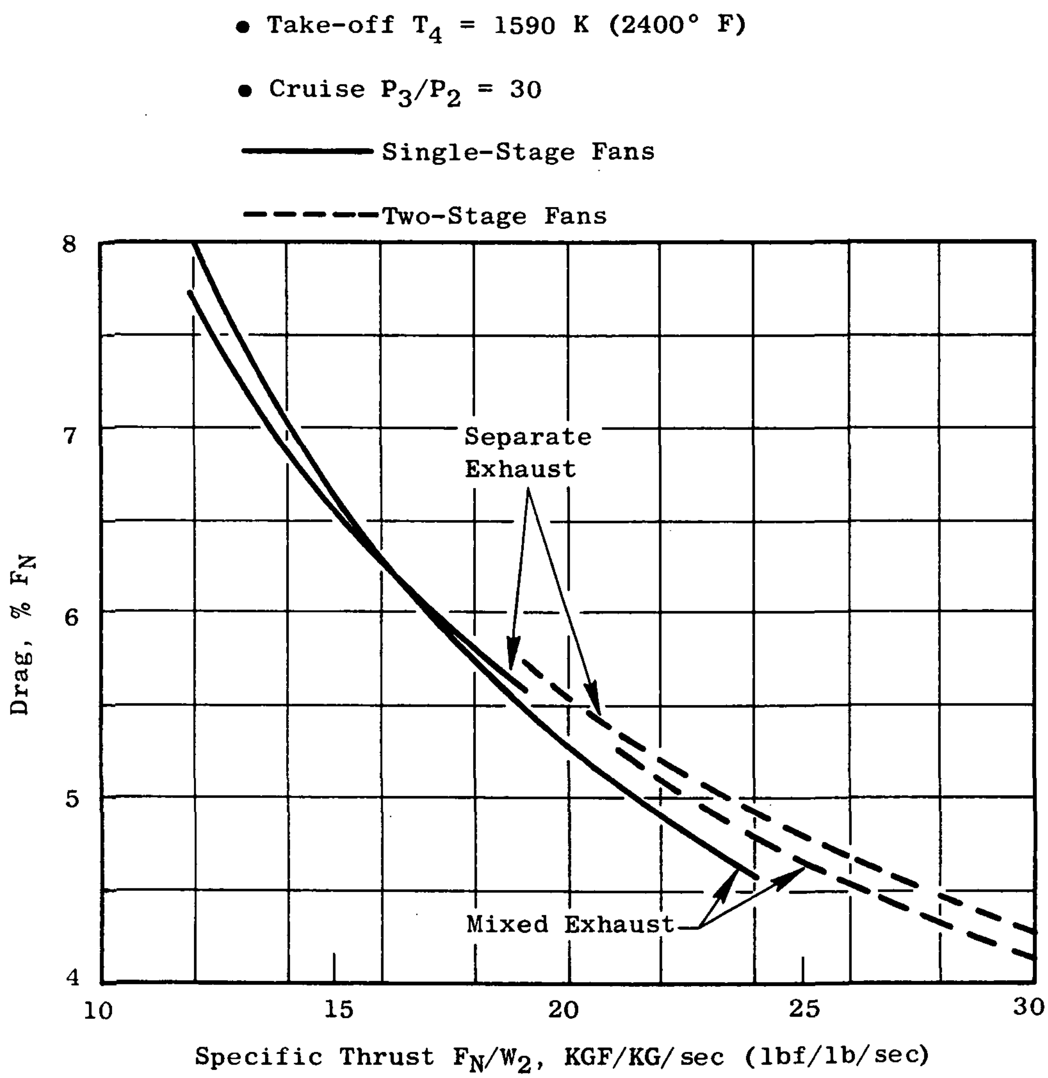


Figure 9. Influence of Specific Thrust on Mach 0.98 Cruise Drag.

Weight and Cost Estimates

Weight estimates for the parametric family of engines were obtained systematically by using a component-by-component weight buildup. Well established component reference weights reflecting design and materials technology applicable to the late 1970's were used in each case, then individually scaled to the required size and corrected for the following effects:

- Tip speed
- Pressure level
- Temperature level (change of material where required)
- Annulus area
- Stage loading
- Radius ratio
- Number of stages
- Aeromechanical stability (fan chord)

Items included in the bare engine and in the installation weights are listed in Table VII. Note that the mixer weight is included as an installation item and, therefore, is not part of the bare engine weight in this breakdown. Intrinsic to the mechanical design procedures established is a consistent level of design technology.

Costs were obtained in a similar fashion with known component costs for the reference components scaled to the required size for each parametric engine and adjusted for the number of stages where applicable. Cost differences thereby reflect specific engine configuration differences, but do not include cost differences associated with advanced technology such as higher temperature materials. These latter cost differences were judged too uncertain to introduce in the parametric trends, as were the cost differences associated with advanced manufacturing techniques.

NOISE

Noise Prediction Procedures

Because of the large number of engines to be considered in the Task I parametric study, the prediction of source noise levels and nacelle suppression were made with the use of simplified design charts. These design charts were developed from available empirical experience at the time of the study. In these charts, approximate but direct relationship between noise constituent PNdB and the design variable of interest is established. The salient frequency characteristics have been explicitly taken into consideration whenever such

TABLE VII. COMPONENTS CONSIDERED IN WEIGHT AND COST ANALYSIS.

Basic Engine	Installation
Fan Rotor Fan Stator Booster Rotor Booster Stator	Inlet Fan Cowl } Nacelle Core Cowl }
Fan Containment and Casing	Fan Reverser
Fan Frame	Primary Spoiler (If Required)
Low Pressure Shaft	Mixed Exhaust (Where Used)
Core Compressor Rotor Core Compressor Stator	Mounts
Combustor Combustor Casing	Suppression Wall Inlet Splitter(s) } (Where Used) Exhaust Splitter(s) }
Core Turbine Rotor Core Turbine Stator	Aircraft Accessories and Equipment§
Fan Turbine Rotor Fan Turbine Stator Fan Turbine Frame	
Bearings and Sumps and Engine Controls and Accessories	
Gooseneck	

§ Not included in installed cost.

frequency characteristics can be defined and their effect on PNdB can be generalized.

The advantage of being able to work directly with PNdB level is obvious. In general, some sacrifice is made in terms of calculation precision by ignoring the detail spectral content. On the other hand, the present state-of-the-art knowledge very seldom permits precise prediction of spectal characteristics of fan noise in the first place. Therefore, so long as noise prediction procedures must rest on approximate empirical ground, the correlation may just as well involve PNdB directly, providing that certain important and known spectral features are taken into account (e.g., blade passing frequency).

It is noted that since the completion of Task I, some of the design and prediction methods used during Task I have been updated. No attempts have been made to redo and/or change the Task I results. Thus, certain details in the noise analysis may appear to be inconsistent between Task I and Task II studies. In general, however, the overall conclusions and engine selections based on Task I were not affected by this consideration.

The steps involved in the noise calculations leading to the airplane systems EPNdB noise levels are outlined in flow chart form in Figure 10, and the basic study ground rules and assumptions are listed in Table VIII. Noise estimates as a function of specific thrust (between 12 and 30) were obtained for mixed exhaust configurations for the base cycle only [P_3/P_2 = 30, T_4 = 1590° K (2400° F) at takeoff], since cycle pressure ratio and temperature have only very minor effects on noise. Separate exhaust configurations would tend to exhibit only slightly higher noise levels at the same specific thrust (higher jet noise of the order of 1 dB for the energy extraction selected and somewhat higher fan noise because of both higher fan pressure ratio and higher fan tip speed). However, these effects are sufficiently small that the reader need only be aware that these differences do exist and should be considered in borderline cases.

Noise Suppression Treatment

Quiet nacelles were defined with consistent amounts of sound suppression treatment to cover the range of noise level specified; i.e., FAR part 36 to FAR part 36 minus 20 EPNdB. In general, two levels of suppression are considered for each engine; i.e., nacelle inlet and exhaust wall treatment only, and wall treatment plus inlet and exhaust splitters. The amount of suppression realized for the cases of interest is summarized in Table IX.

To anticipate technology advances by the 1985 time period, system noise also was obtained with an assumed 5 PNdB reduction in fan noise. This noise reduction reflects a possible combination of fan noise reduction at the source and improved suppression effectiveness.

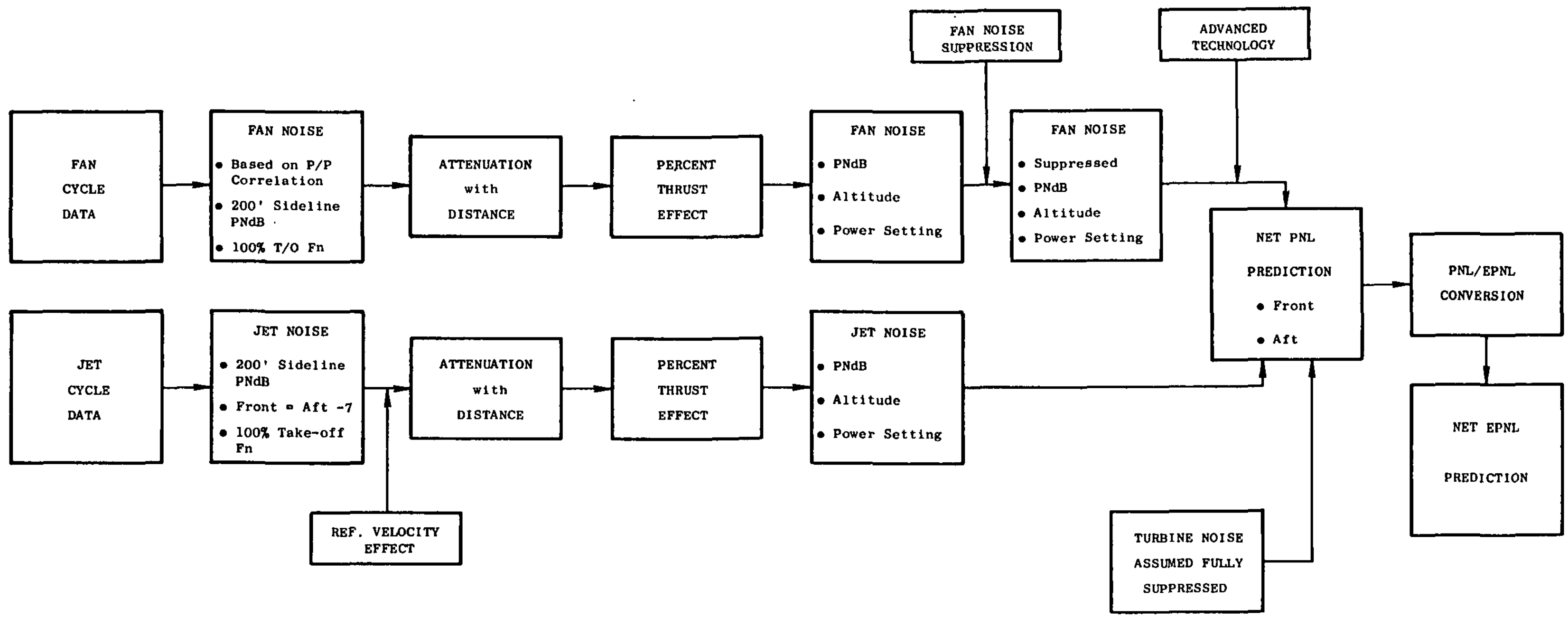


Figure 10. Task I - Noise Calculation Flowchart.

TABLE VIII. TASK I NOISE GROUND RULES AND ASSUMPTIONS.

JET NOISE

- Mixed flow configurations used in Task I noise study.
- Static jet noise prediction based on scale model mixer nozzle test results and correlation with other data.
- Mixed flow jet noise about 1 PNdB higher than equivalent conical nozzle (due to imperfect mixing).
- Maximum sideline radiation angle [$\approx$ 1.920 rad (110°) to 2.094 rad (120°)] from inlet.
- SAE flight effect used.

FAN NOISE

- 5 PNdB source reduction for advanced technology (1985).
- Single-stage fan noise level based on empirical correlation of noise data from NASA QEP fans and other GE fans and engines, both high- and low-speed fans.
- For single-stage fans, front end controlled, aft noise 2 PNdB lower.
- Single-stage fan, 2-chord spacing, no IGV.
- Two-stage fan, 5 PNdB higher, based on limited test data, aft noise controlled.
- Two-stage fan, 1-chord spacing, no IGV.

TURBINE NOISE

- For Task I, assumed suppressed to level below fan noise level, specific means to be defined in Task II.

FAN NOISE SUPPRESSION

- Based on GE suppression design guides.
- Inlet and aft duct walls treated.
- Splitter length criteria:
    - Inlet - L/H $\approx$ 4
    - Aft - L/H $\approx$ 5.5
- MDOF treatment at inlet (better MPT control):
    - SDOF - Aft

PNdB TO EPNdB CONVERSION

- Based on current high bypass commercial experience, more detailed study in Task II.

TABLE IX. TASK I NOISE SUPPRESSION SUMMARY.

Specific Thrust		PNdB			
		Wall Only		Wall + Splitters†	
F_N/W_2	No. Fan Stages	Front	Aft	Front	Aft
12	1	6	5	11	12
15	1	6	6.5	12	14.5
19	1	6	9	13.5	17
21	1	6	11	14	18
21	2	6	9	12	15
24	2	6	10	12	16
30	2	6	13	10‡	17

† All have 2-ring inlets, (L/H = about 4); one aft splitter, (L/H = about 5.5).

‡ 1-ring inlet; no aft splitter.

EXHAUST EMISSIONS

Objectionable exhaust emissions from jet engines include carbon particulates as soot or smoke, carbon monoxide (CO), unburned or partially oxidized hydrocarbons (H/C's), and oxides of nitrogen (NO_x). The exhaust emissions study objectives for the advanced transport technology engines were specified by NASA as follows:

Pollutant		Objective
CO		40
Unburned H/C's		8 g/Kg fuel
NO	Idle	3
Smoke	Takeoff	SAE Number 15

Figure 11 shows peak smoke characteristics of existing General Electric engines as a function of overall engine pressure ratio for engines developed prior to 1966 and for engines developed since 1966 or currently under development. Carbureting combustion systems similar to other low smoke carbureting systems recently developed are planned for ATT engines. With these systems, the smoke objective level specified for ATT engines can be met.

Carbon Monoxide and Unburned Hydrocarbons

Maximum CO and hydrocarbon emissions levels occur at ground idle conditions where combustion efficiency is lowest. Figure 12 shows the relationship between CO and hydrocarbon emission levels and combustion efficiency. The ATT engine objective levels for these emissions are equivalent to an idle efficiency level of about 98.3%. This curve also shows that various combinations of CO and hydrocarbons are possible at a given efficiency. These combinations are interrelated in that high hydrocarbon levels must be accompanied by low CO levels and vice versa. Combustion inefficiency as a function of fuel/air ratio at idle conditions for a spray atomizing combustion system is shown in Figure 13. This trend is typical for carbureting systems also. From this curve and advanced component test data, curves for estimated idle emission levels as a function of fuel/air ratio can be constructed as shown in Figure 14. This curve shows that fuel/air ratio at idle must be increased beyond the normal level to meet the ATT engine idle emissions objectives. This can be done by either bleeding compressor exit air during idle or by a suitable combustor design where richer mixtures can be obtained locally. Test results for an advanced combustor with compressor exit bleed flow are shown in Figure 15. It is expected from these data that the required idle combustion efficiency of 98.3% (to meet the idle emissions objectives) can be obtained with approximately 15% compressor discharge bleed.

Oxides of Nitrogen (NO_x)

Although CO and hydrocarbon emissions objective levels are expected to be achieved for the ATT engines, the oxides of nitrogen emissions level

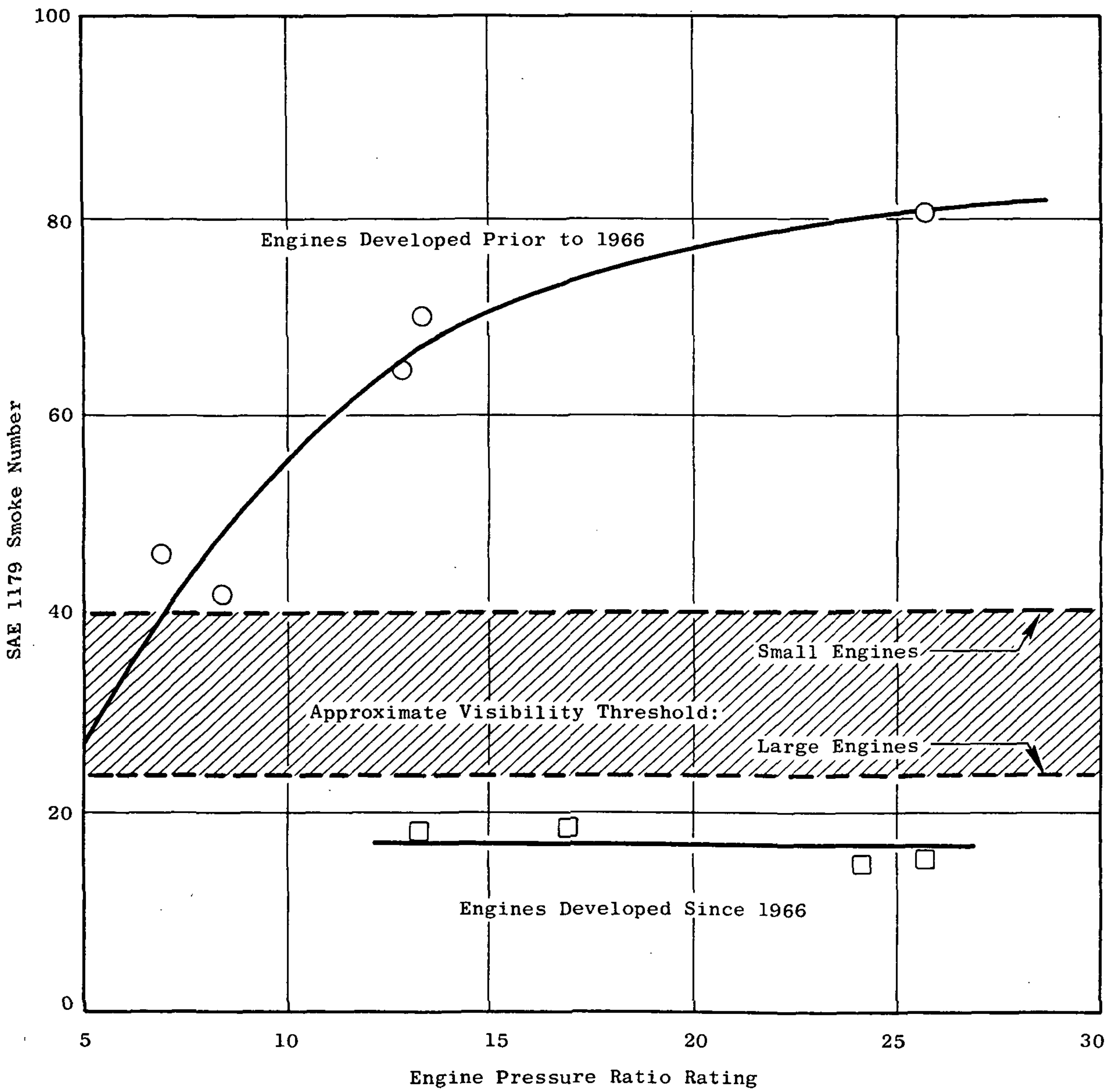


Figure 11. Comparison of Peak Engine Smoke Emission Characteristics.

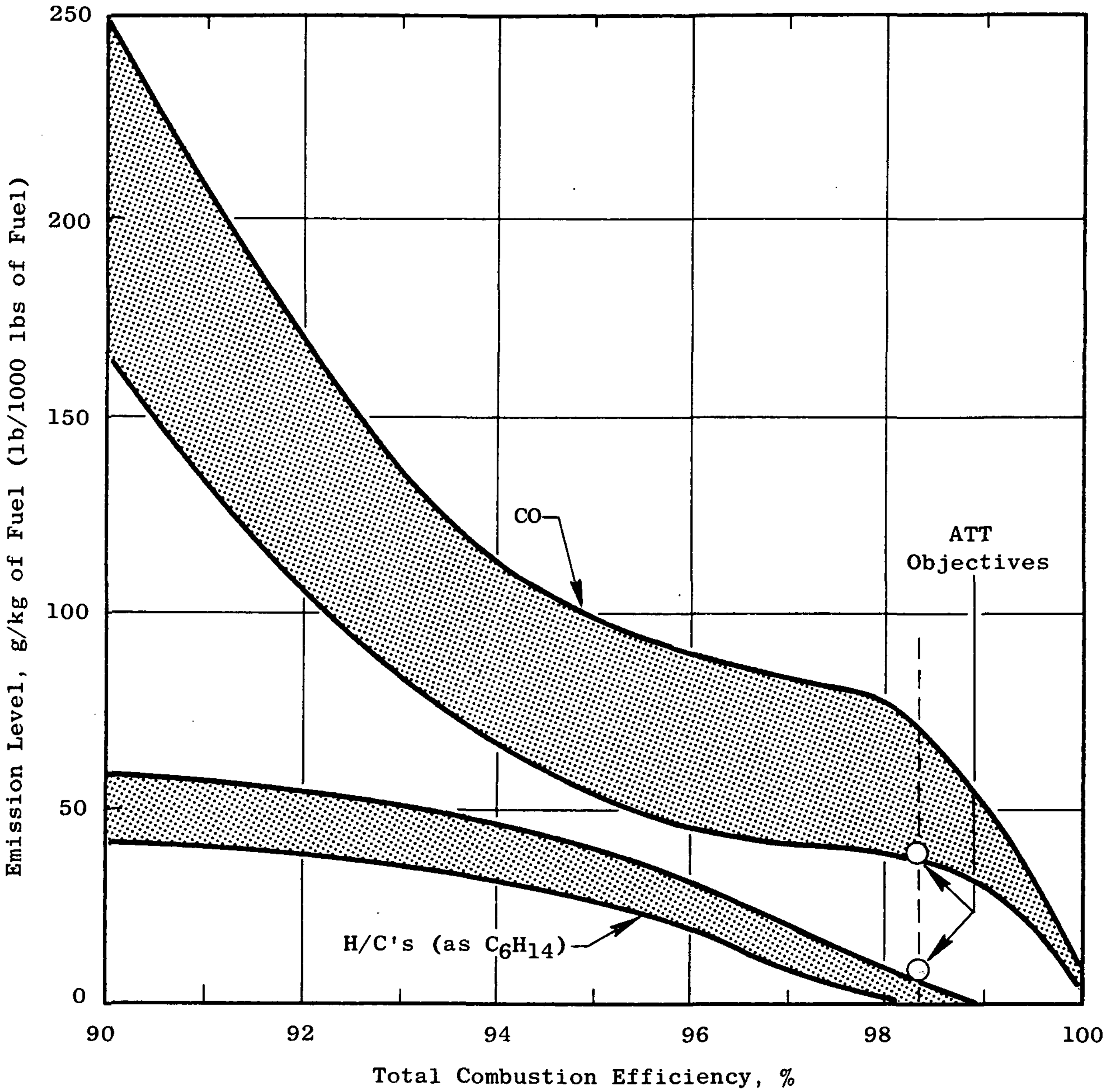


Figure 12. Typical Relationships Between Combustion Efficiency and Levels of CO and H/C Emissions.

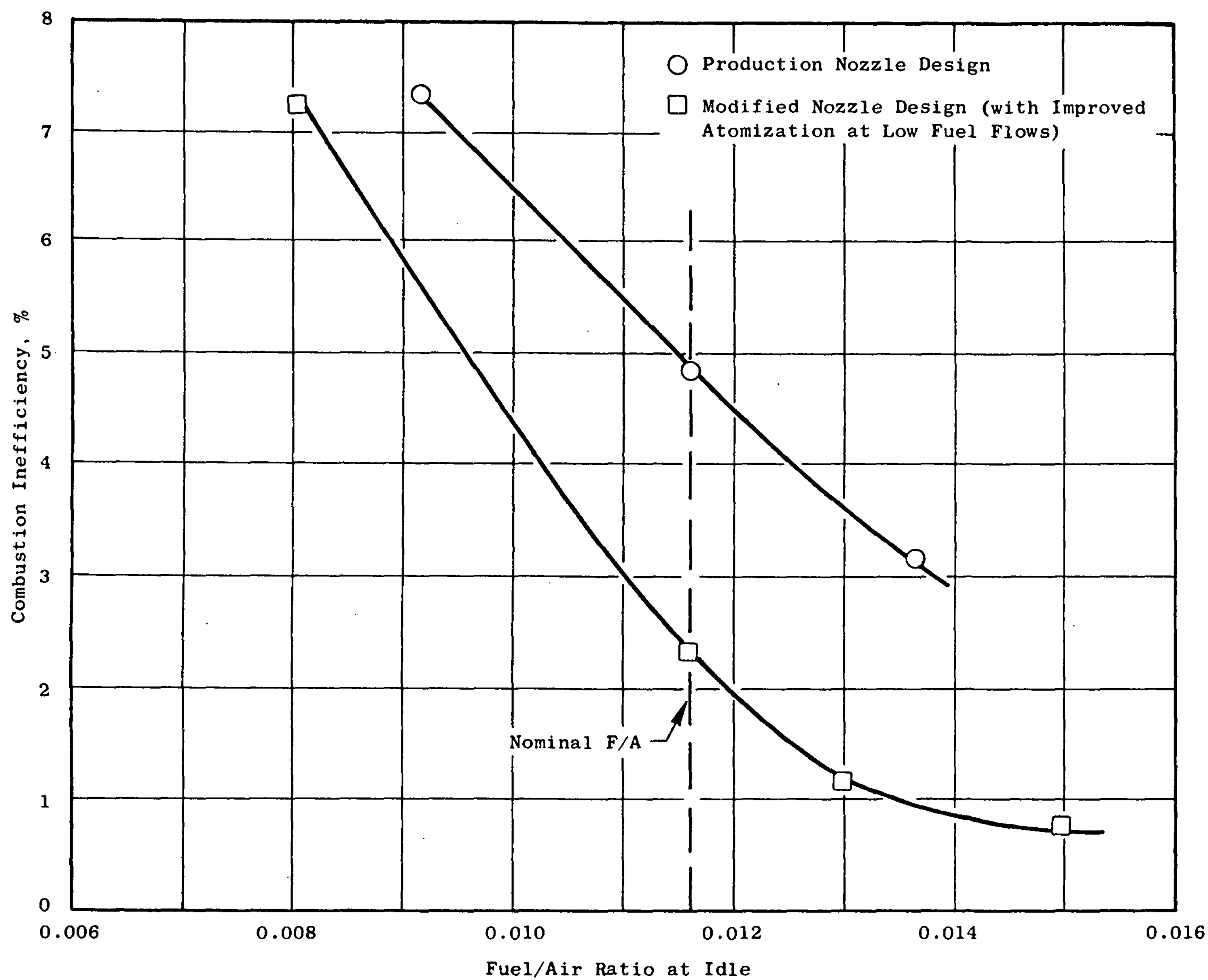


Figure 13. Typical Combustion Efficiency Characteristics for a Current Engine.

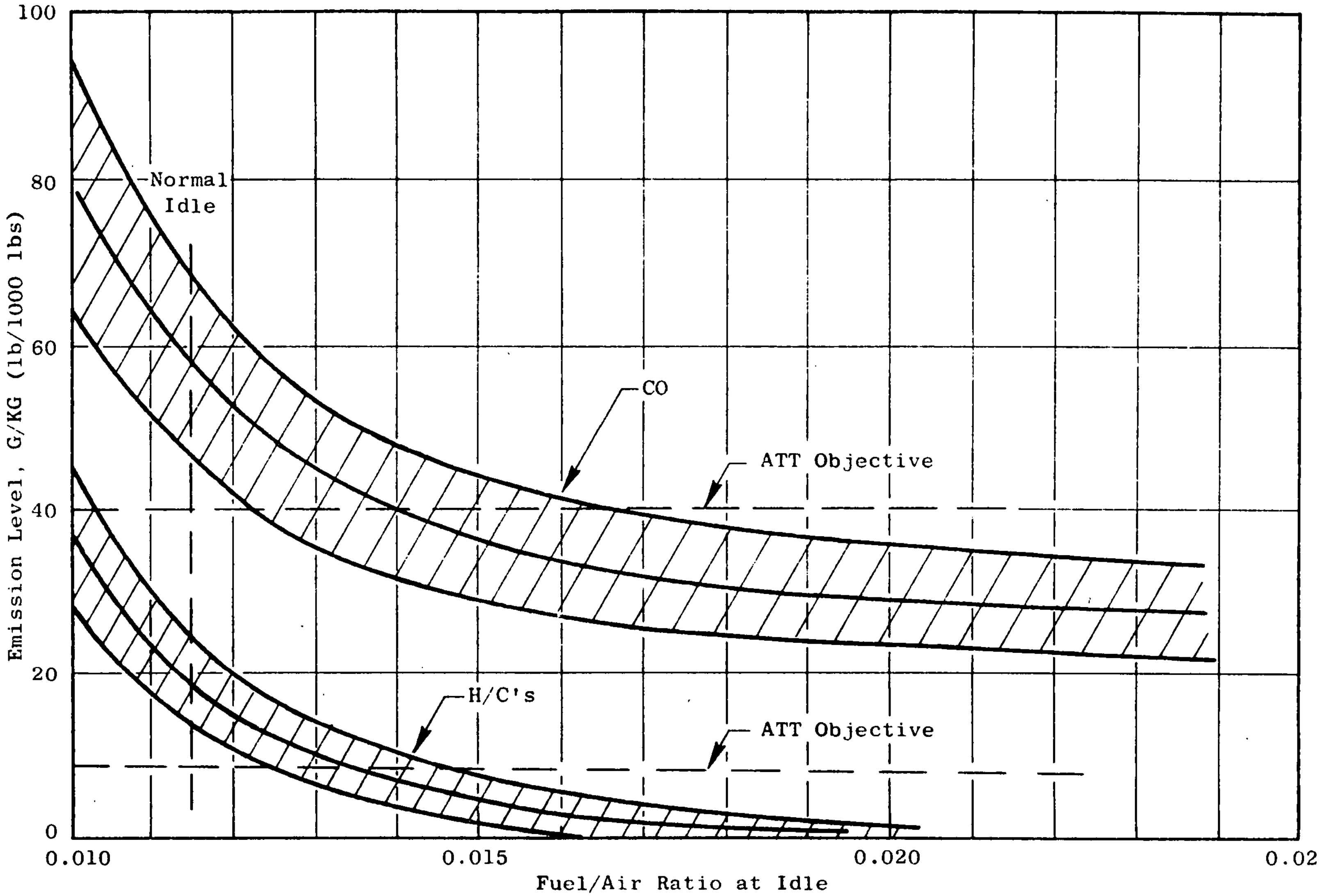


Figure 14. Predicted Emission Levels at Idle Conditions.

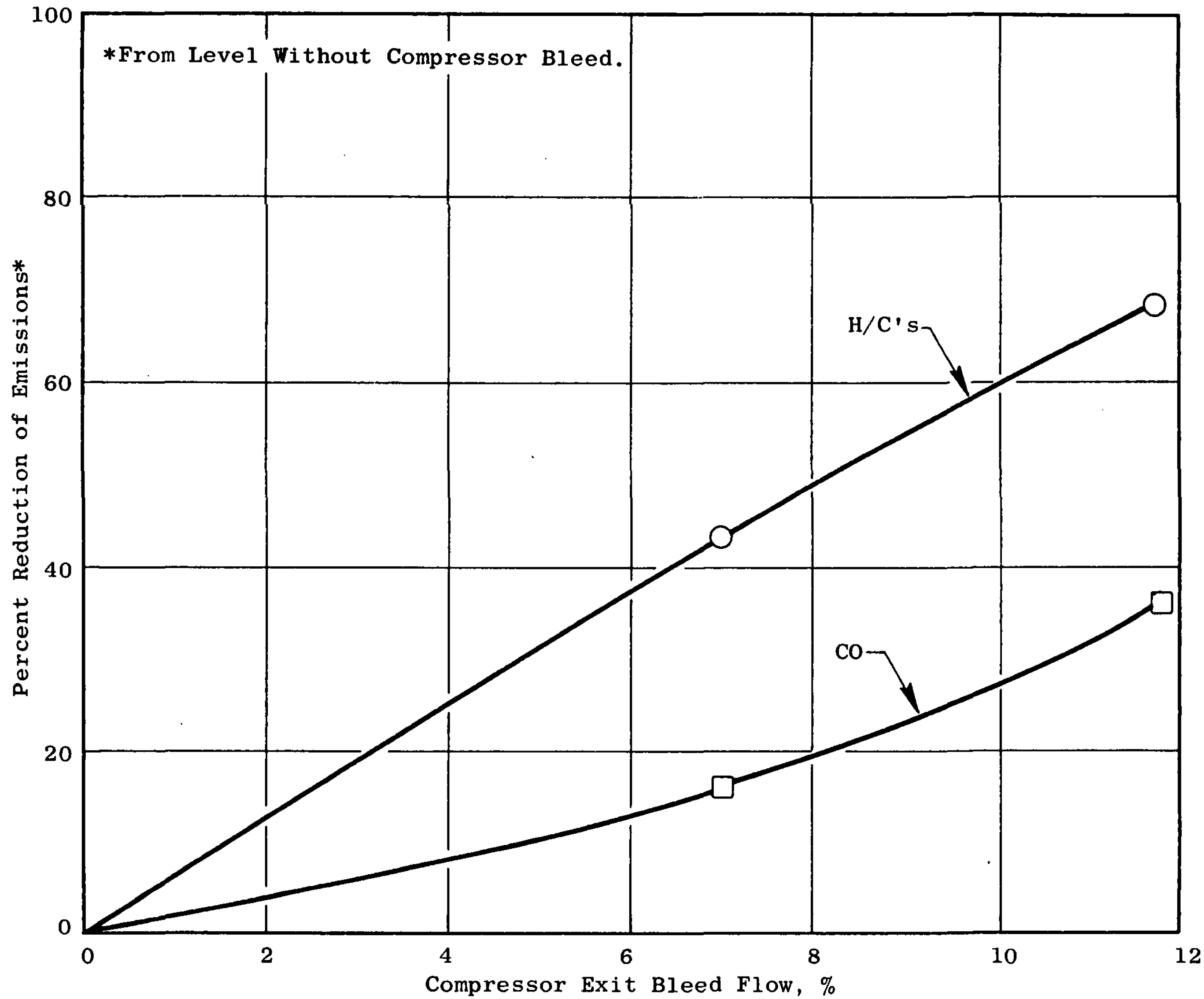


Figure 15. Advanced Combustor Full Annular Test, Effect of Compressor Exit Bleed Flow Extraction on Idle Emissions.

target does not appear to be achievable unless combustor water injection is used. Figure 16 shows the NO_x emission trends, in terms of nitric oxide (NO), at take-off power setting as a function of engine pressure ratio for conventional combustion exit temperatures [less than 1700° K (2600° F)]. The predicted characteristics for advanced carbureting combustors also are indicated. These curves show the trends and high levels of NO_x emissions for current cycle temperatures and pressure ratios. Higher fuel/air ratios associated with higher cycle temperatures [1920° K (3000° F)] are expected to result in increased gas residence times at high temperatures [above 1370° K (2000° F)] within the combustor and, thus, are estimated to result in up to 50% higher NO_x levels than for lower outlet temperature combustors at the same combustor inlet conditions. Thus, meeting the very low NO_x emissions target in these advanced, high pressure ratio, and high cycle temperature engines with combustor design improvements alone is not considered likely. However, significant reduction in NO_x emissions do appear attainable with advanced carbureting combustors and with primary combustion stoichiometry control.

In order to achieve the theoretical degree of NO_x suppression, the water must be fully evaporated and uniformly dispersed with the fuel in the dome. To determine the degree to which the theoretical suppression can be approached in practice, reliance is placed on component test data, typified by Figure 17. A 40% reduction appears feasible for water injection of one percent of combustor airflow.

The predicted effects of water injection on NO_x emissions, based on test data and on theory, are compared in Figure 18 for two cycles of interest. Indications are that water rates of the order of 2 - 3% of combustor airflow will be needed for advanced carbureting combustors to meet the objective emission level of 3 g of NO per kg of fuel.

BASIS OF ENGINE EVALUATION

The parametric engines were evaluated using relative aircraft gross weight and differences in Direct Operating Cost (DOC) and Return on Investment (ROI) relative to a base case. For this purpose, two host aircraft were defined having the major characteristics shown in Table X. The Mach 0.98 design is the high performance configuration defined by NASA. Both aircraft are configured with three rear-mounted engines. The payload and range selected for this purpose are in the middle of the ranges that the ATT airframe contractors were to exercise in their parametric studies.

The definition of the host aircraft and their selection were reviewed with the ATT airframe contractors before proceeding with the generation of mission trade factors. The mission trade factors for the effects of installed sfc pod weight and price variations were obtained for completely rubberized vehicles holding payload, range, and initial cruise altitude constant. These trade factors then were used to evaluate the differences between the parametric engines studied, relative to a base case. All engines were scaled to the installed cruise thrust required by each airplane as shown in Table X.

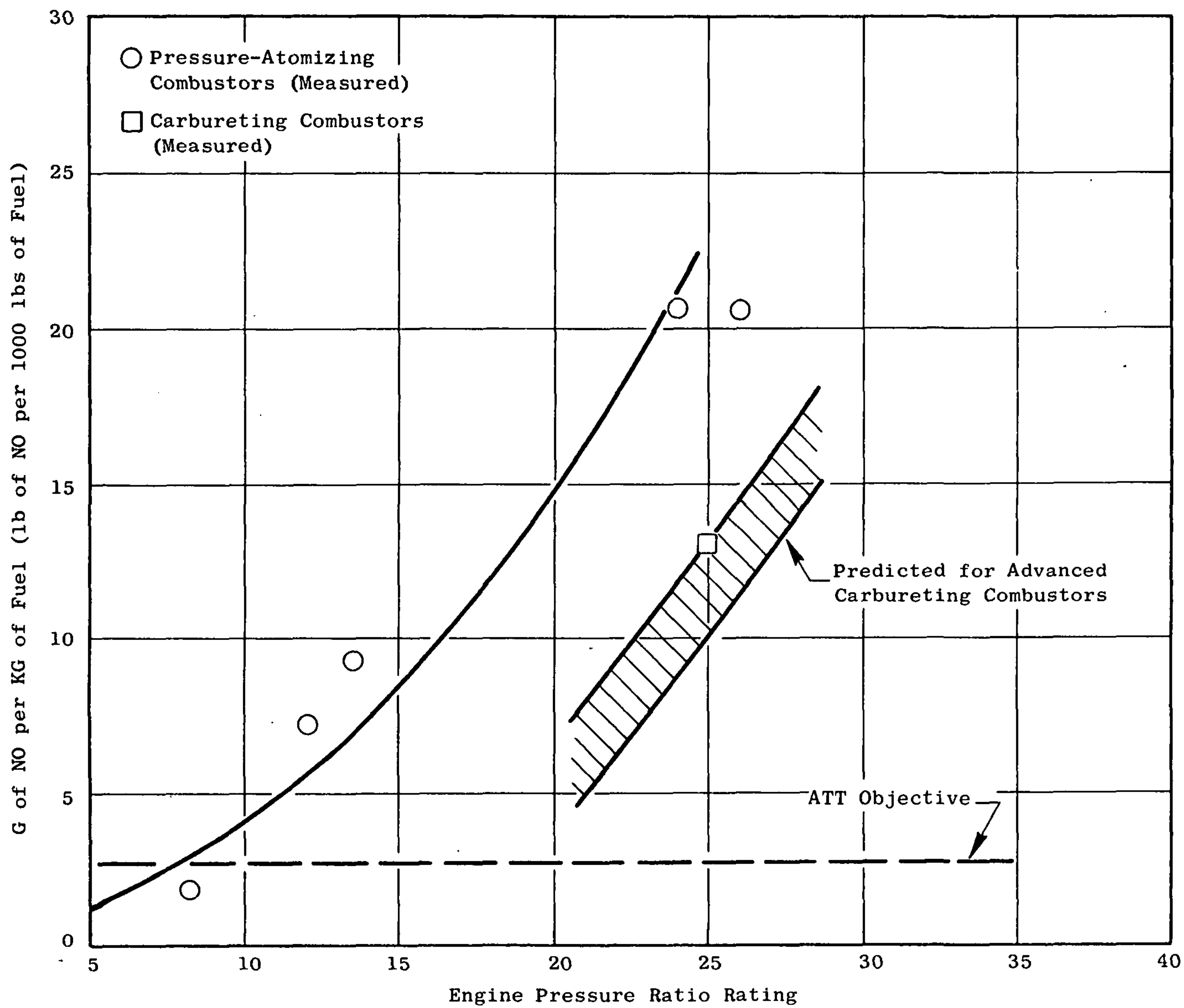


Figure 16. NO_x Emission Trends at Sea Level Static Full Power Operation.

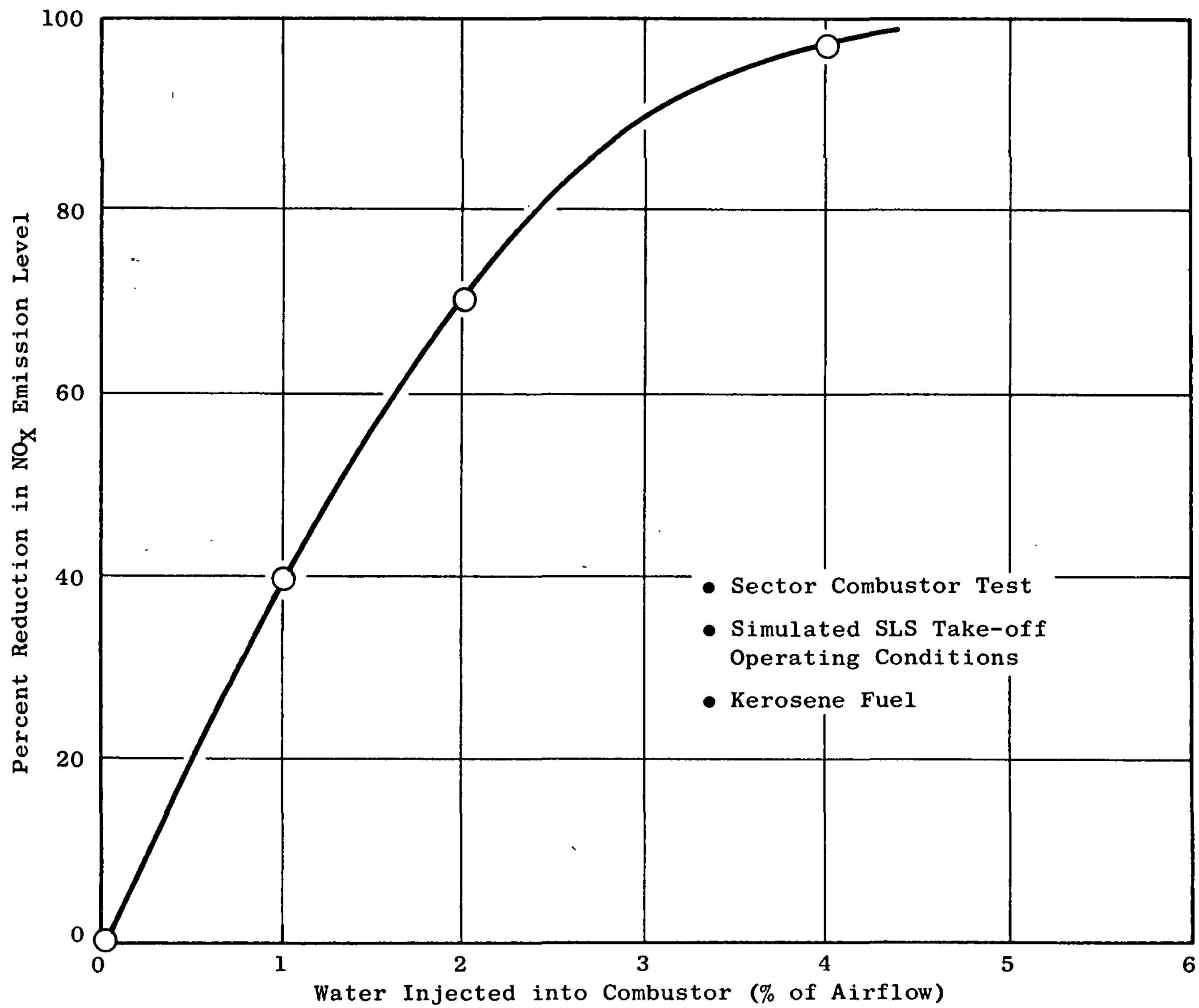


Figure 17. Effect of Water Injection on NO_x Emissions Characteristics of Carbureting Combustor.

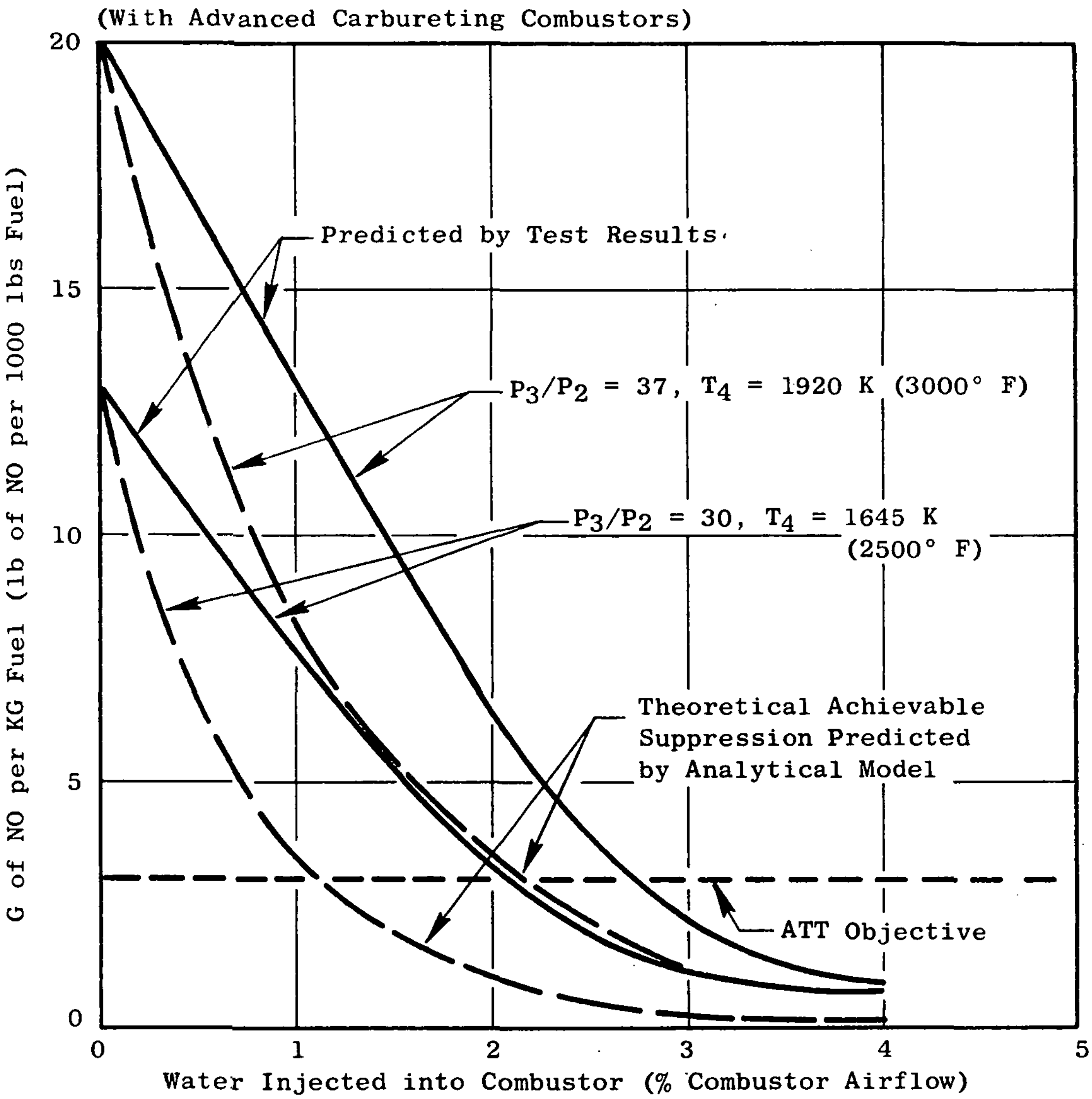


Figure 18. Predicted Effects of Water Injection on NO_x Emissions at Sea Level Static Takeoff.

TABLE X. HOST AIRPLANE CHARACTERISTICS.

Cruise Mach Number	0.98	0.90
Range, km (Nautical Miles)	5555 (3000)	5555 (3000)
Payload, kg (lbs)	27,200 (60,000)	27,200 (60,000)
Number of Engines	3	3
Wing Loading, W/S, kg/m^2 (lbs/ft^2)	591 (121)	591 (121)
Take-off Gross Weight, kg (lbs)	193,200 (426,000)	186,600 (411,000)
Begin Cruise Altitude, m (ft)	11,890 (39,000)	11,280 (37,000)
F_{N1}/Engine at Cruise Altitude, N (lbs)	41,150 (9250)	40,030 (9000)
at 12,190 m (40,000 ft)	39,230 (8820)	34,700 (7800)

The economic ground rules used in the formulation of Direct and Indirect Operating Costs and Return on Investment are summarized below:

- Direct Operating Cost (DOC)

  The 1967 ATA formulation of DOC estimates was used with the following adjustments:

  1. Crew costs and labor rates were modified per NASA inputs.

  2. Engine labor man hours and material costs were modified to reflect General Electric experience.

  3. A 15 year depreciation period to zero residual value was used as specified by NASA.

  4. Aircraft utilization was assumed to be a constant 3600 hours per year.

- Indirect Operating Cost

  The procedures developed and published by Lockheed in Report LW70-500R, dated May 1970, were used.

- Return on Investment (ROI)

  Return on investment was determined using the discounted cash flow method. In this method, the yearly cash flows are determined and a discounting factor found such that the sum of the discounted cash flow equals the original investment.

The mission trade factors for the Mach 0.98 airplane are shown in Table XI and for the Mach 0.90 airplane in Table XII.

RESULTS AND DISCUSSION OF RESULTS

Major Parametric Study Trends - (Economic Aspects)

The effects of specific thrust (fan size selection or bypass ratio for a given core technology), engine configuration (mixed versus separate exhaust), and cycle variations (technology level) on airplane economics are presented together to provide a better perspective and easier reference for direct comparison of these important variables. These trends are first presented without noise constraints to permit identification of the best engines or cycles on the basis of mission performance alone. For this purpose, all engines are compared with the same level of noise treatment consisting of wall suppression treatment only.

TABLE XI. MISSION TRADE FACTORS FOR MACH 0.98 A/C, TASK I.

Change	Effect Upon		
	TOGW	DOC	ROI†
+1% Installed sfc	+0.76%	+0.72%	-0.32%
+227 kg (+500 lb) Weight per Engine	+1.10%	+0.65%	-0.30%
+ $10,000 Basic Engine Price	---	+0.14%	-0.08%
+ $10,000 Reverser Price	---	+0.09%	-0.06%
+ $10,000 Other Installation Price	---	+0.07%	-0.06%

Note: All engines scaled to an installed cruise thrust of 41,150 N (9250 lbs) at 11,890 m (39,000 ft), M = 0.98.

† ROI - A 1% change in ROI represents an absolute change as from 25% to 26%.

TABLE XII. MISSION TRADE FACTORS FOR MACH 0.90 A/C, TASK I.

Change	Effect Upon		
	TOGW	DOC	ROI†
+1% Installed sfc	+0.75%	+0.73%	-0.32%
+227 kg (+500 lb) Weight per Engine	+1.10%	+0.70%	-0.30%
+ $10,000 Basic Engine Price	---	+0.15%	-0.09%
+ $10,000 Reverser Price	---	+0.09%	-0.07%
+ $10,000 Other Installation Price	---	+0.08%	-0.07%

Note: All engines scaled to an installed cruise thrust of 40,030 N (9000 lbs) at 11,280 m (37,000 ft).

† ROI - A 1% change in ROI represents an absolute change as from 25% to 26%.

The relationships between specific thrust, bypass ratio, and fan pressure ratio for the range of cycle conditions of most interest and for both mixed and separate exhaust engine configurations are shown in Figure 19. Since fan inlet flow is constant, the effect of higher cycle temperature at any specific thrust level is to shrink the core size required to match the cycle such that bypass ratio increases as indicated in Figure 19(A). For a given cycle, the variation in bypass ratio between mixed and separate exhaust configurations is small, as shown in Figure 19(A), but the separate exhaust configuration requires a significantly higher fan pressure ratio [Figure 19(B)] for a reasonable cycle energy extraction which yields near-optimum performance, as discussed further on pages 50 and 59. This characteristic difference between mixed and separate exhaust cycles has a direct implication on the maximum specific thrust cycle that can be achieved with a single-stage fan. In this study, a maximum fan pressure ratio of 1.9 was established as a reasonable limit for advanced single-stage fan designs. For this maximum value of fan pressure ratio, the highest cruise specific thrust is approximately 17 for the separate exhaust cycle, compared to 21 for the mixed exhaust case. Note that large cycle differences (temperature and cycle pressure ratio) cause only small variations in the fan pressure ratio for any value of specific thrust, as illustrated for the mixed exhaust cycles in Figure 19(B).

Specific fuel consumption trends versus specific thrust for the same cycles are shown in Figure 20 without drag (bare engine) and with isolated pod drag (installed). Figure 20(A) shows the performance advantage of the mixed exhaust cycles over the separate exhaust cases for the same cycle temperature and overall pressure ratio ($\sim$2%). Per the previous discussion, the transition from a single- to a two-stage fan occurs at a lower specific thrust for the separate exhaust configuration as shown. The lower sfc shown for the two-stage fan at the transition point is due to its higher efficiency (lower tip speed at same pressure ratio). Figure 20(B) shows the significant performance benefits of using a higher technology core for a mixed exhaust configuration (2-1/2% to 3% on an installed basis).

The corresponding weight and price trends for these engine families are presented relative to the mixed exhaust base case in Figures 21 and 22, showing weight and price decreasing with smaller fan size (higher Fn/W_2), as expected. Bare engine weight refers to turbomachinery weight with the mixer weight and associated ducting included in the pod weight. Besides the discontinuity due to the transition from a single- to a two-stage fan discussed above, another discontinuity (indicated by an asterisk) occurs on the pod weight and price curves for the mixed exhaust configuration, reflecting the substitution of a full exhaust thrust reverser for a fan-only reverser. In this study, 30% reverse thrust was arbitrarily selected as the minimum reverse thrust acceptable. For a given bypass ratio, a mixed exhaust system with a fan-only reverser and fixed exhaust nozzle can provide a substantially higher reverse thrust than a separate exhaust configuration due to the aerodynamic thrust spoiling of the core flow that occurs. When the fan flow is blocked off, the core flow is discharged alone through the large exhaust nozzle area, yielding the benefits associated with a large variation in core exhaust area of a separate exhaust system without the mechanical complexity of this feature. For a mixed exhaust

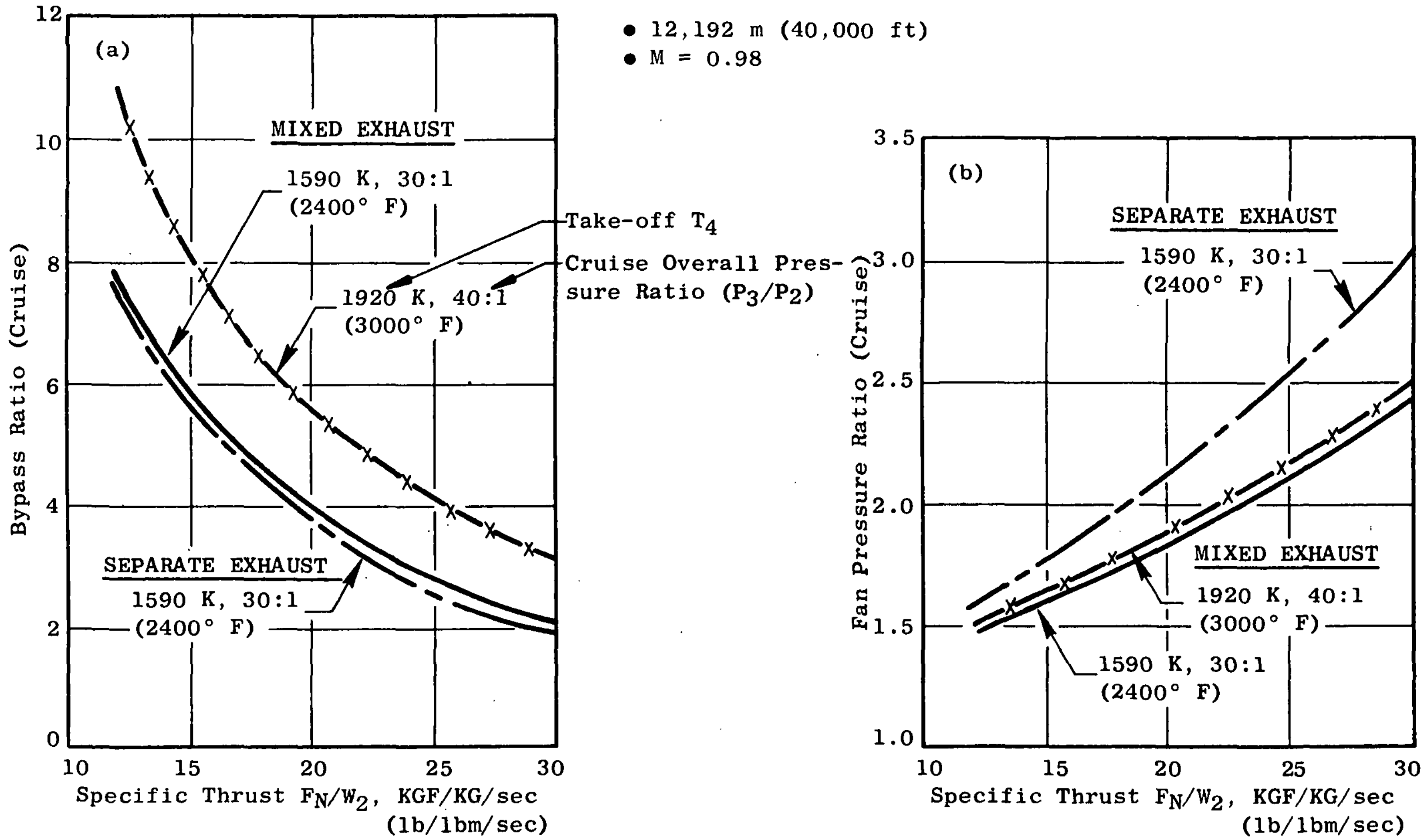


Figure 19. Engine Parametric Study Cycle Trends Versus Specific Thrust.

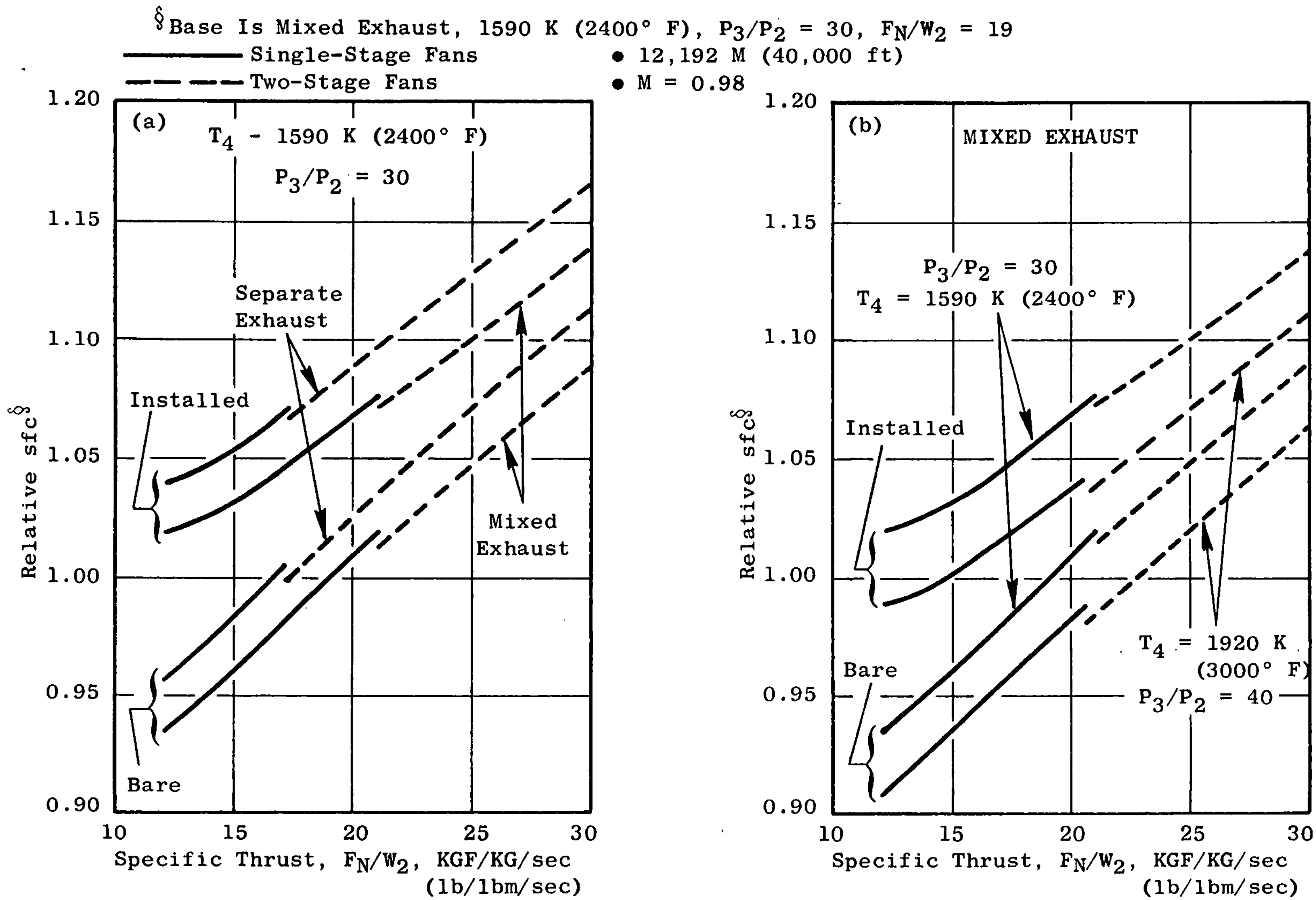
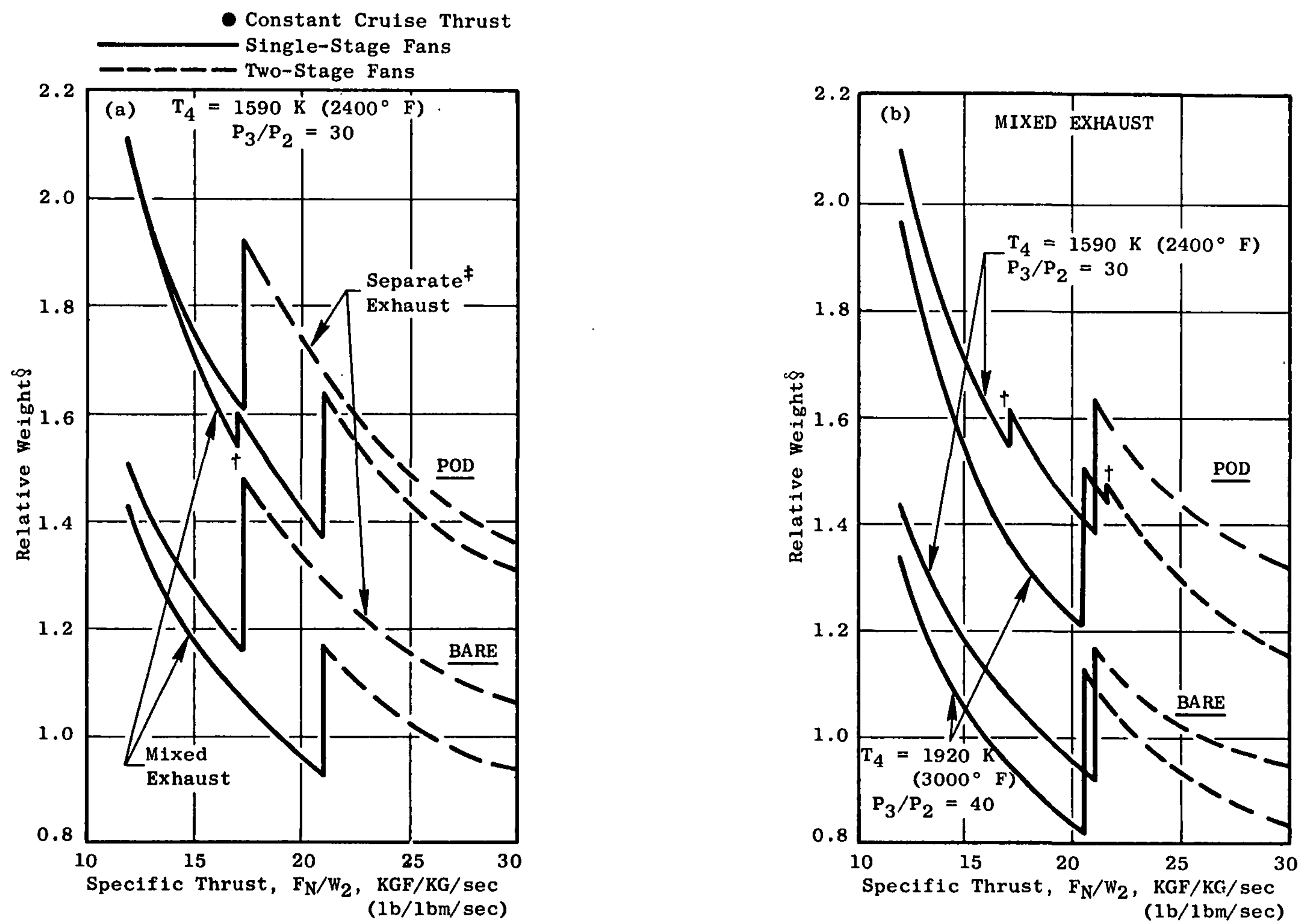


Figure 20. Engine Parametric Study Performance Trends Versus Specific Thrust.

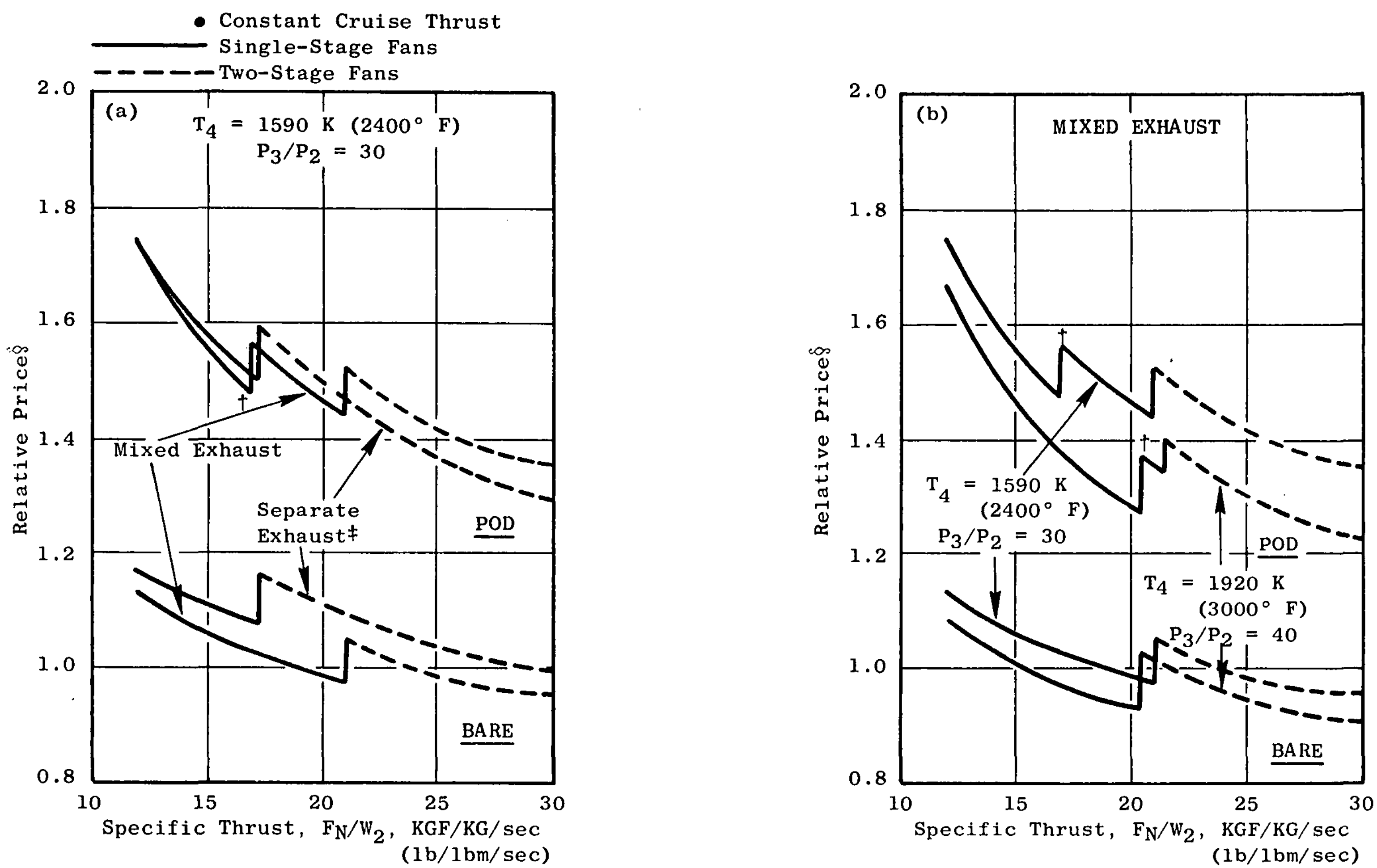


§ Base Is Mixed Exhaust, 1950 K, P_3/P_2 = 30, F_N/W_2 = 19
(2400° F)

† Transition from Fan Reverser to Full Reverser

‡ Fan Reverser and Core Spoiler

Figure 21. Engine Parametric Study Weight Trends Versus Specific Thrust.



§ Base Is Mixed Exhaust, 1590 K (2400° F), P_3/P_2 = 30, F_N/W_2 = 19
† Transition from Fan Reverser to Full Reverser
‡ Includes Fan Reverser and Core Spoiler

Figure 22. Engine Parametric Study Price Trends Versus Specific Thrust.

configuration, a full reverser is needed for bypass ratios less than about 5; for a separate exhaust configuration, the addition of a core spoiler is needed to achieve 30% reverse thrust for bypass ratios below about 8-1/2. (No discontinuity occurs in the separate exhaust curves shown at this temperature since bypass ratio is less than 8-1/2 at the lowest specific thrust, as shown in Figure 19.)

Significant weight and cost penalties are indicated for a two-stage fan configuration compared to a single-stage fan. These differences are due to the fan itself plus the associated weight and cost effects due to differences in fan containment, structure, fan turbine, fan shaft, and nacelle.

The large payoff of higher core technology (higher T_4 and cycle pressure ratio) is shown for the mixed exhaust family of engines in Figures 21(B) and 22(B). It directly reflects the smaller core size needed when cycle temperature is increased. The same effects, of course, are applicable to separate exhaust systems.

The combined effects of sfc and pod weight variations presented above yield the aircraft gross weight trends shown in Figure 23 as a function of engine specific thrust for the Mach 0.98 airplane. All engines are scaled to the same installed cruise thrust and all have wall suppression treatment only.

The mixed-exhaust trend shows that the lowest aircraft gross weight without noise constraints is obtained at the highest specific thrust achieved with a single-stage fan. Because of the higher engine and installation weight associated with the two-stage fan configuration, a significant aircraft gross weight penalty is incurred, as indicated in Figure 23(A). In addition, for the same level of noise suppression treatment, two-stage fan configurations are more noisy at a given specific thrust and, therefore, require more treatment to achieve the same noise level.

The separate exhaust cycles exhibit the same general trends versus specific thrust as the mixed exhaust cycles, but indicate a significant gross weight penalty at any value of specific thrust. This is primarily due to higher cruise sfc's. The transition from a single- to a two-stage fan occurs at a substantially lower specific thrust (17 versus 21) where fan pressure ratio is also 1.9. This is a fundamental difference between the two cycles which allows the mixed exhaust to reach higher specific thrusts with a single-stage fan. Higher specific thrust could be achieved with the separate exhaust by decreasing the cycle energy extraction at the expense of higher jet noise. While this may be acceptable at low specific thrust where jet noise is not controlling, it would not help at high values of specific thrust where the jet noise contribution to the overall noise is significant and eventually controls. It also should be noted that the energy extraction of the mixed flow cycle also could be reduced in a similar manner with comparable effects on specific thrust and less impact on jet noise.

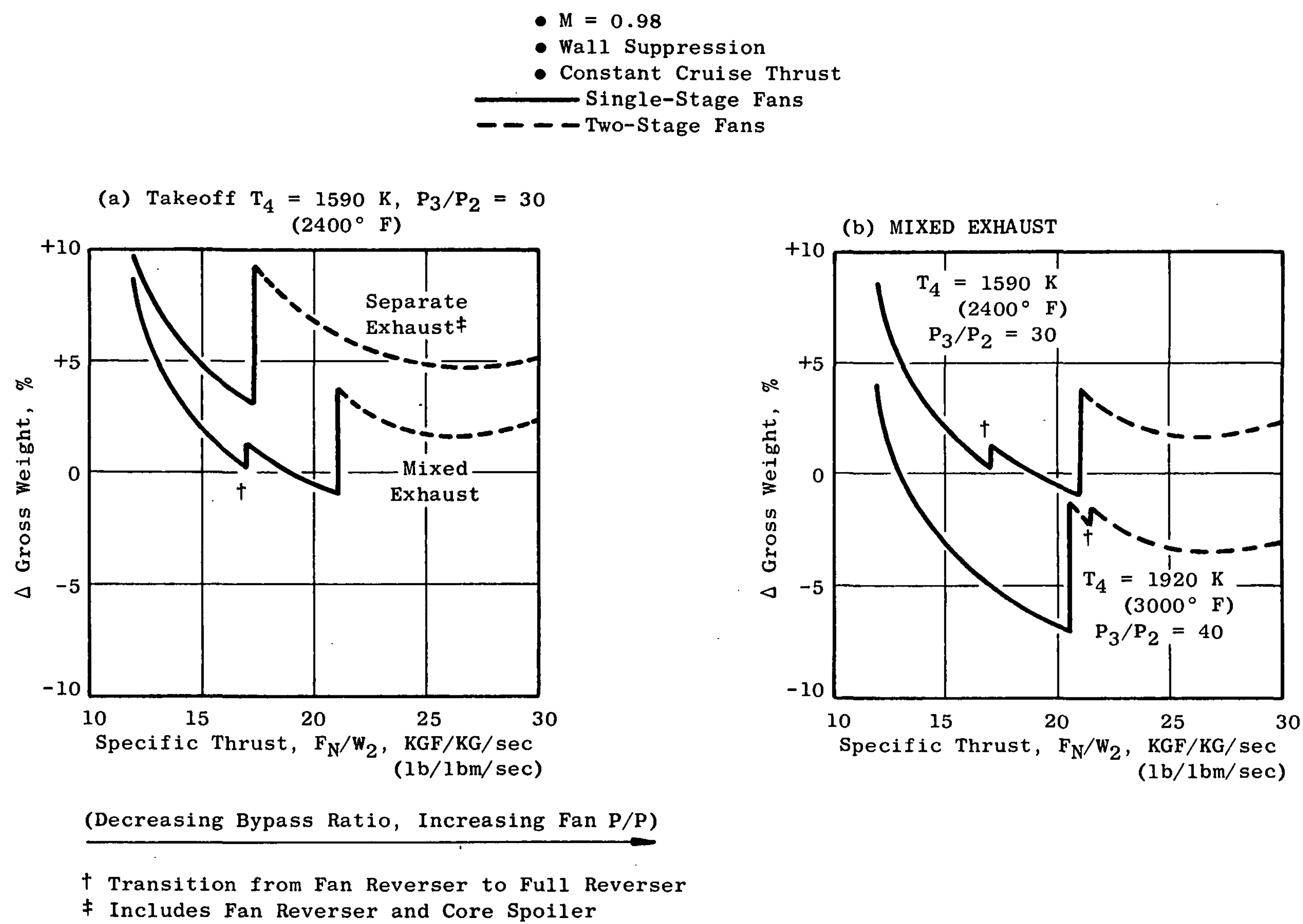


Figure 23. Engine Parametric Study Aircraft Gross Weight Trends Versus Specific Thrust (M = 0.98).

Figure 23(B) illustrates the significant payoff of higher cycle temperature for a mixed exhaust cycle when advanced cooling technology and higher temperature materials consistent with the 1985 time period are used. The higher cycle pressure ratio is thermodynamically compatible with the higher temperature (thermal efficiency), but its contribution to the improvement in mission merit factor is relatively small (∿15% of the total benefit shown at a specific thrust of 19). This is better illustrated in Figures 24 and 25 which show the impact of higher core technology over a wide range of cycle pressure ratio and cycle temperature at the reference engine specific thrust of 19. These characteristics are just as applicable to other values of specific thrust and to separate exhaust systems. It should be noted that the choice of specific thrust for best mission performance is hardly affected by cycle temperature and pressure ratio variations [Figure 23(B)]; and, therefore, the choice of fan size can be selected independently of these variations.

These effects, of course, are applicable to the separate exhaust configuration and apply at other flight speeds as well.

Changes in direct operating cost (DOC) and return on investment (ROI) relative to the base cycle include the price trends shown in Figure 22. These economic trends are shown for the same parametric variations in Figures 26 and 27. Note that changes in ROI are shown as absolute differences from a reference ROI level such that a 1% change represents a change from 25% to 26%, for example. The economic trends exhibit the same characteristics as the aircraft gross weight trends and lead to the same conclusions.

Effect of Cruise Mach Number on Optimum Specific Thrust

A parametric evaluation similar to that conducted for the Mach 0.98 airplane was made for a Mach 0.90 airplane to determine the effect of cruise speed on fan size selection and the corresponding fan pressure ratio and bypass ratio for a given core technology. This excursion was conducted for the reference cycle* using the Mach 0.90 host airplane mission derivatives and scaling rematched engines to the lower cruise thrust required by the host airplane shown in Table X.

Engine performance, weight, and price trends are shown in Figure 28 relative to the base case normalized at M = 0.90. The resulting aircraft gross weight variation and economic trends are presented in Figure 29. Compared to the trends shown in Figures 23, 26, and 27 for the M = 0.98 cruise speed, it can be noted that the curves begin to flatten out somewhat sooner as a function of specific thrust indicating, as expected from propulsive efficiency considerations, that the optimum fan size and bypass ratio would be slightly higher for the Mach 0.90 application than for the higher cruise speed. The best economics without noise constraints are still realized at the maximum fan pressure ratio achievable with a single-stage fan for a given reverser configuration, but there are less inhibitions to back off from that cycle since the economic penalty is smaller than at M = 0.98. Because of its lower initial cruise altitude, the Mach 0.90 airplane tends to require a higher takeoff-to-cruise thrust ratio which, along with noise considerations, would favor the selection of a somewhat lower specific thrust (lower fan pressure ratio and higher bypass ratio).

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* Takeoff T_4 = 1590° K (2400° F); cruise cycle pressure ratio = 30; mixed exhaust.

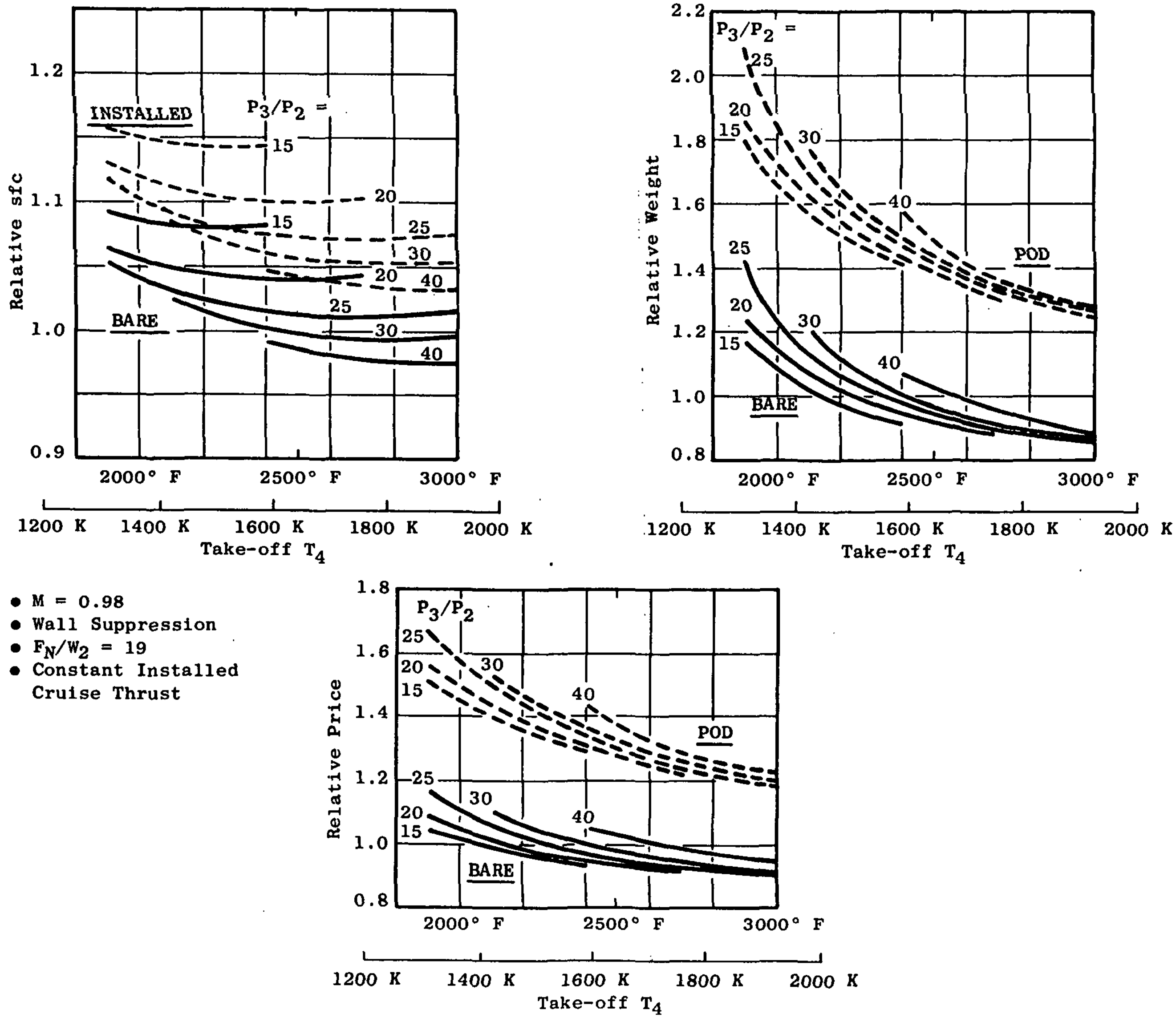


Figure 24. Engine Parametric Study Cycle Temperature and Pressure Ratio Effects on SFC, Weight, and Price at Constant Specific Thrust (M = 0.98).

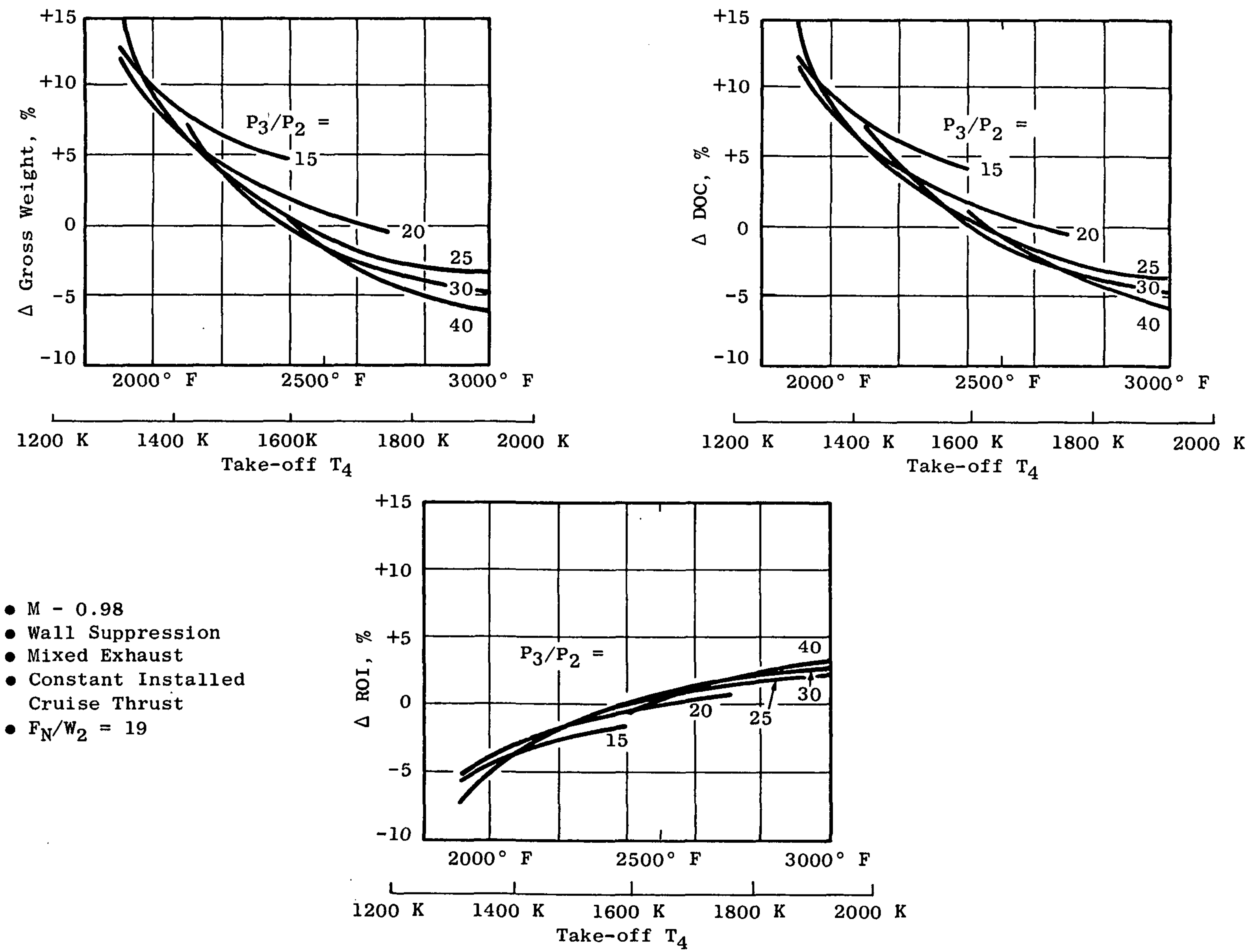
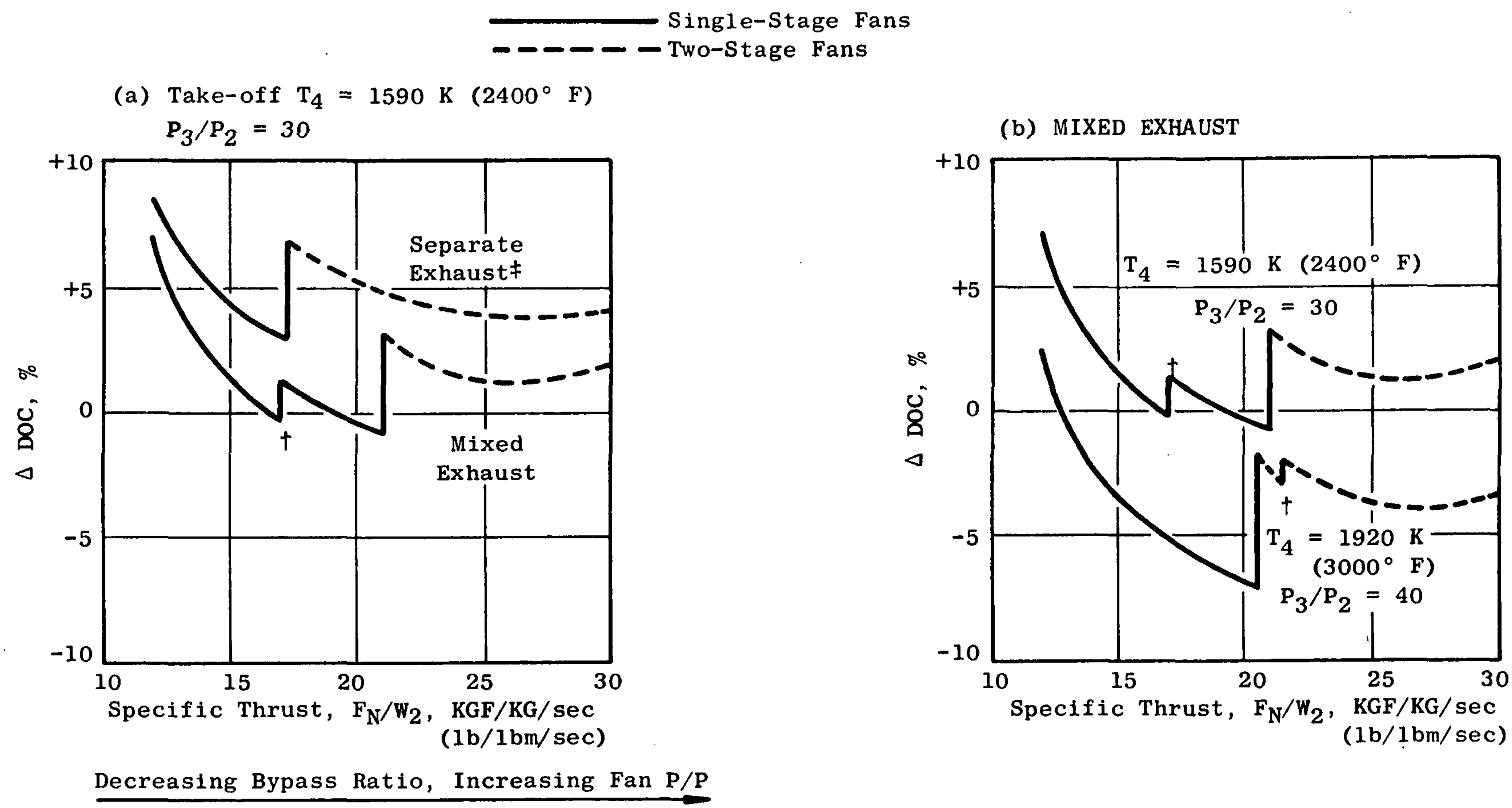
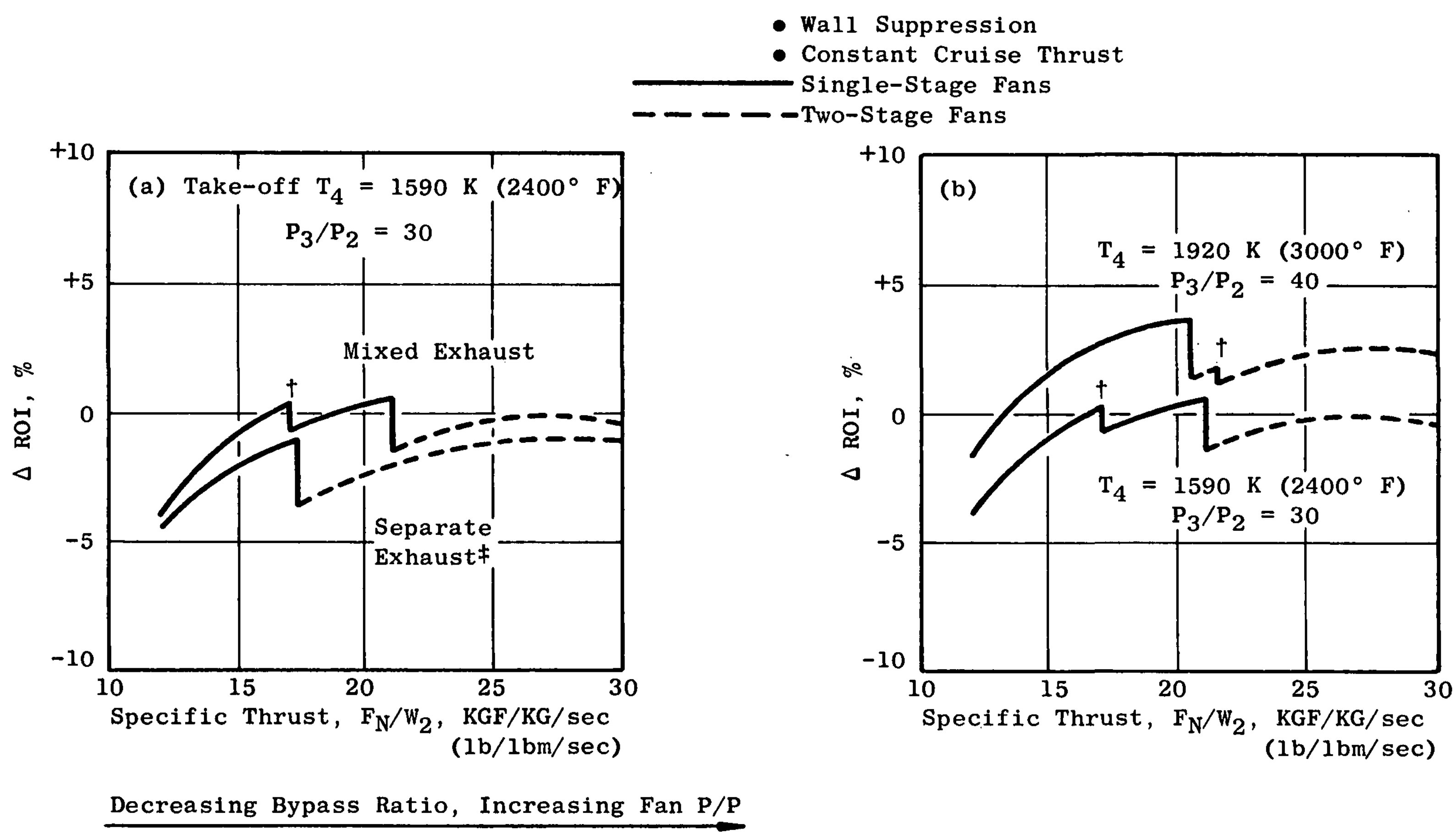


Figure 25. Engine Parametric Study Cycle Temperature and Pressure Ratio Effects on Aircraft Gross Weight, DOC, and ROI at Constant Specific Thrust (M = 0.98).



† Transition from Fan Reverser to Full Reverser
‡ Includes Fan Reverser and Core Spoiler

Figure 26. Engine Parametric Study Direct Operating Cost Trends Versus Specific Thrust (M = 0.98).



§ Δ ROI - Absolute Difference - i.e., 1% as from 25% to 26%
† Transition from Fan Reverser to Full Reverser
‡ Includes Fan Reverser and Core Spoiler

Figure 27. Engine Parametric Study Return on Investment Trends Versus Specific Thrust (M = 0.98).

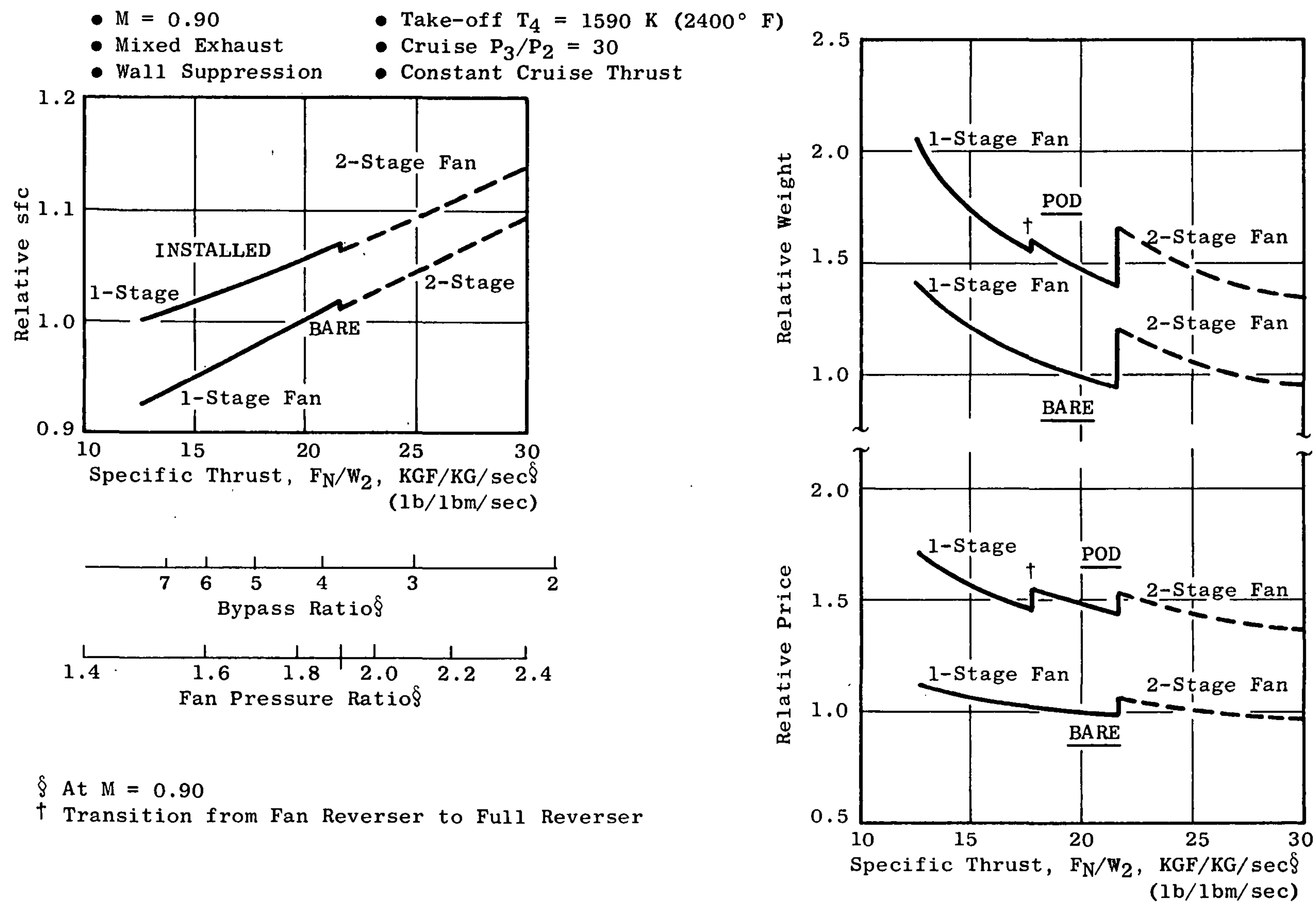
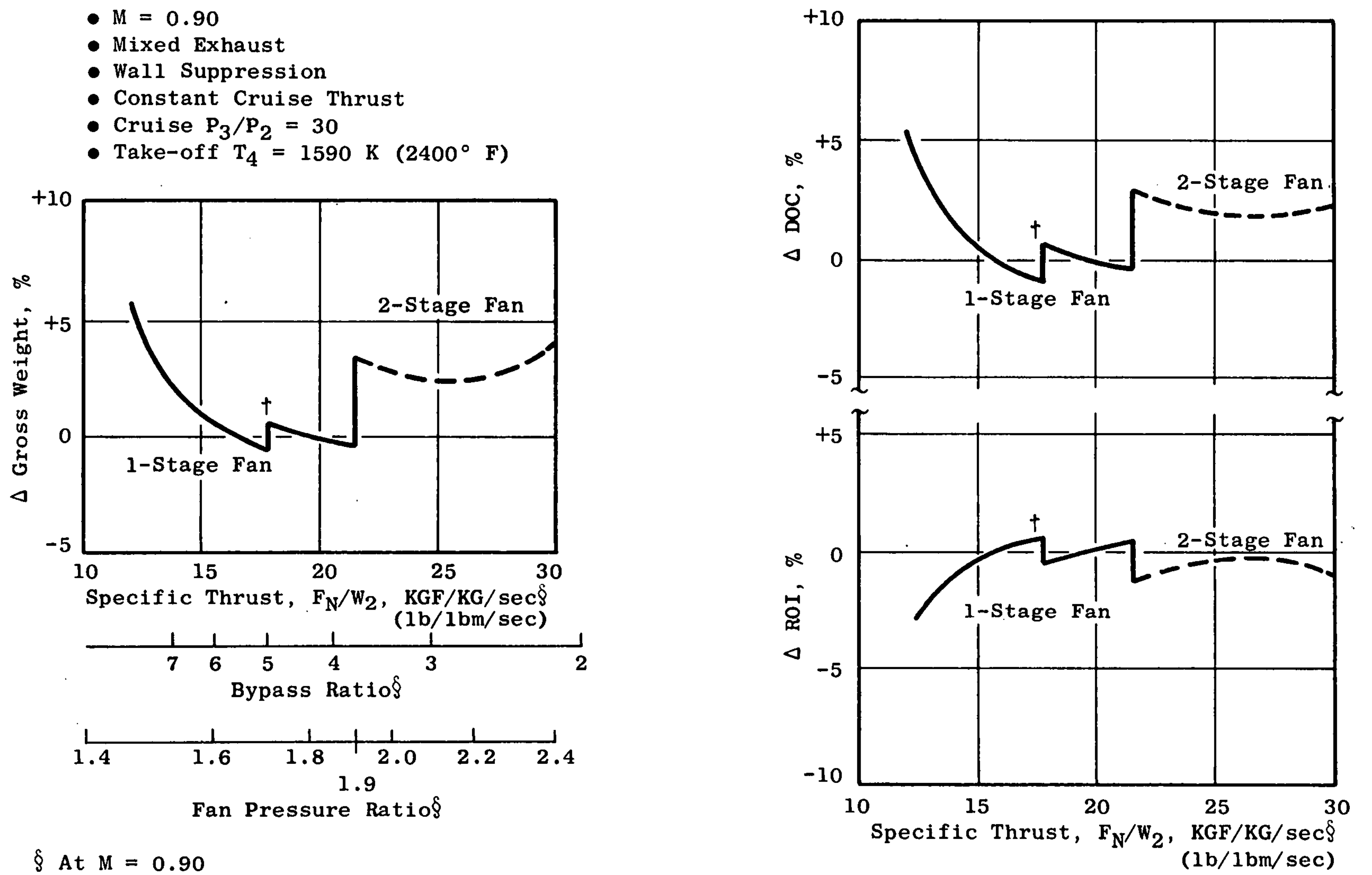


Figure 28. Engine Parametric Study Trends of sfc, Weight, and Price as a Function of Specific Thrust.



§ At M = 0.90
† Transition from Fan Reverser to Full Reverser

Figure 29. Engine Parametric Study Trends of Aircraft Gross Weight, DOC, and ROI as a Function of Specific Thrust (M = 0.90).

Effect of Energy Extraction - Separate Exhaust

Core energy extraction for a constant specific thrust of 15 was varied over a range of exhaust jet velocity ratio, V_9/V_{29}, to determine the sensitivity of this parameter on mission merit factors. An energy extraction corresponding to a jet velocity ratio of 1.3, which yields minimum as shown in Figure 30(A), was used throughout the parametric engine study and was used as the reference case in this exercise.

Energy extraction was varied by changing fan pressure ratio, as shown on the abscissa of Figure 30(A). Bypass ratio essentially remained constant over the full range of extraction considered. Excursions in energy extraction on either side of the thermodynamic optimum resulted in relatively small increases in with engine weight and price favorably affected in the direction of lower extraction. Except for jet noise, there was no incentive to select an energy extraction above the thermodynamic optimum level. Results shown in Figure 31 indicate that, without noise constraints, economics would benefit slightly by selecting an extraction level somewhat below the thermodynamic optimum (higher jet exhaust velocity ratio). This is consistent with earlier optimization studies conducted at General Electric. However, for high specific thrust cycles which have been shown to be desirable for an ATT airplane, the jet noise contribution to the overall noise becomes a factor (which becomes even more significant for growth versions of the engine) which tends to bias the selection of energy extraction toward higher values than would be chosen on the basis of initial mission performance alone.

On the other hand, in the interest of extending the range of specific thrust achievable with a single-stage fan which was shown earlier to be desirable, lower energy extraction remains an option to be considered. It is clear that the selection of this parameter normally would be made within its most logical range (V_9/V_{29} = 1.3 to 1.5) on the basis of factors other than initial performance alone, since its influence on mission performance and economics is relatively small. However, the choice of the 1.3 value does not affect any of the conclusions reached in this study.

Noise Estimates

Using the ground rules and the prediction procedures described earlier, estimated fan and jet noise constituent levels in PNdB and system noise in EPNdB were obtained for the engine operating conditions at the FAR 36 reference points summarized in Table XIII. These engine operating conditions are based on the 0.98 Mach number host airplane. A given thrust required by the airplane at approach and at power cutback represents different percentages of available thrust, as indicated in the table, due to the different engine lapse rates for the different specific thrust cycles. Note also that the airplane altitude over the noise-measuring point after takeoff varies significantly with engine specific thrust.

Six categories of noise estimates were made, as follows:

- Bare engine noise estimates, current technology

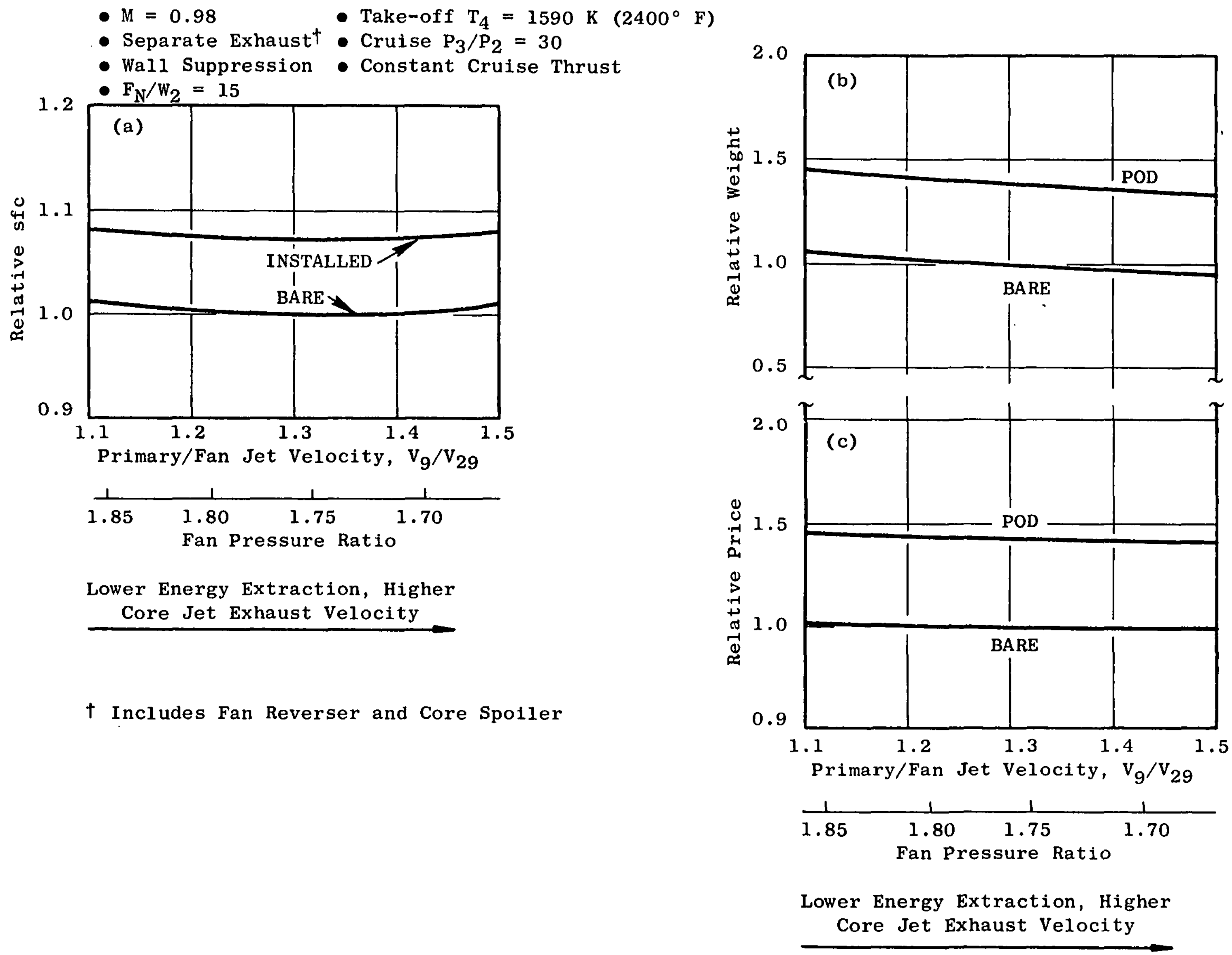


Figure 30. Engine Parametric Study Trends of SFC, Weight, and Price as a Function of Energy Extraction - Separate Exhaust (M = 0.98).

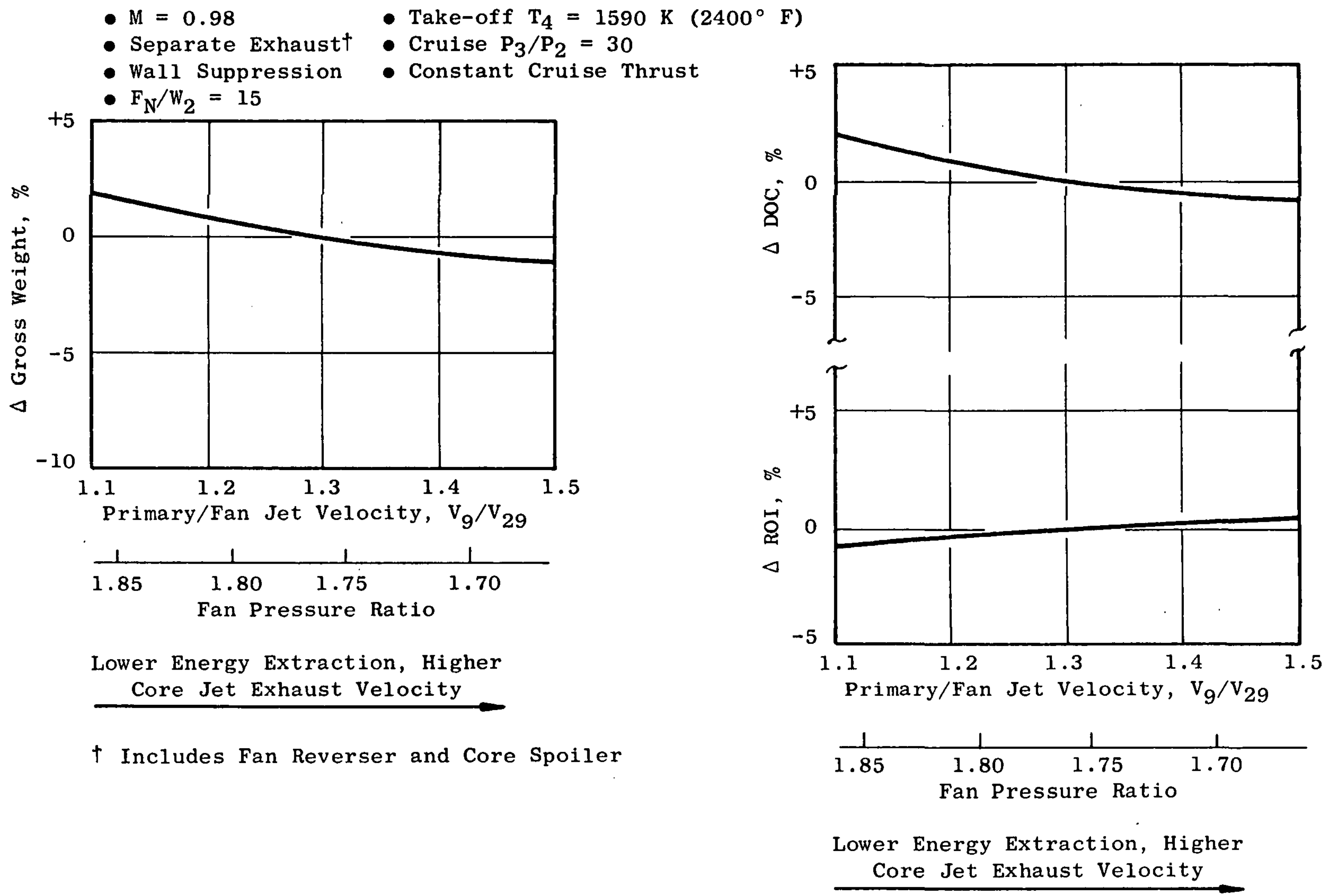


Figure 31. Engine Parametric Study Trends of Aircraft Gross Weight, DOC, and ROI as a Function of Energy Extraction - Separate Exhaust (M = 0.98).

TABLE XIII. ENGINE OPERATING CONDITIONS AT FAR36 REFERENCE STATIONS, TASK I.

- Standard + 14° C Day
- 3 Engines
- TOGW = 193,200 kg (426,000 lbs) (Mach 0.98 Aircraft)
- M = 0.25 at Takeoff
- M = 0.20 at Approach

Specific Thrust Fn/W_2 kgf/kg/sec (lb/lbm/sec)	Take-off Thrust at M = 0.25 Newtons (lbs)	6482 m (3.5 n mi) after Brake Release		1952 m (1 n mi) before Touchdown	
		Altitude meters (feet)	% Take-off Fn (Power Cutback)	Altitude meters (feet)	% Take-off Fn
12	176,100 (39,600)	902 (2960)	60	113 (370)	26.4
15	165,900 (37,300)	817 (2680)	62.5		27.8
19	157,000 (35,300)	689 (2260)	66.5		30.0
21 (1- and 2-Stage fan engine)	153,500 (34,500)	640 (2100)	68.1		30.9
24	148,600 (33,400)	588 (1930)	70.2		32.1
30	140,100 (31,500)	524 (1720)	73.5		34.0

- Nacelle wall suppressed noise estimates, current technology
- Fully suppressed (with splitters) estimates, current technology
- Bare engine estimates, advanced technology (i.e., 5 PNdB fan source reduction)
- Nacelle wall suppressed noise estimates, advanced technology
- Fully suppressed estimates, advanced technology

The resultant EPNdB noise levels for a 3-engine-powered airplane [TOGW = 193,200 kg (426,000 lbs)], expressed in terms of ΔEPNdB relative to FAR 36 levels, are plotted in Figures 32, 33, and 34 as a function of cycle specific thrust (Fn/W_2) for the three FAR 36 reference points and for both current and advanced technology engines. Finally, traded EPNdB levels relative to FAR 36, for both current and advanced technology engines, are plotted as a function of Fn/W_2 in Figure 35.

Key results from the Task I Study and their significance are discussed below.

- Noise Vs. Specific Thrust Trends - In all six categories of noise estimates - from current technology bare to advanced technology fully suppressed - systems noise level in EPNdB generally increases with increasing cycle specific thrust, Fn/W_2. This trend exists at all three FAR 36 reference points. The rate of increase is most rapid where the fan noise is suppressed the most. Two fundamental reasons for this trend are: (1) basic fan and jet source noise levels increase with increases in fan pressure ratio and exhaust velocity, both of which go up with an increase in cycle specific thrust, and (2) airplane/engine matching is such that, to meet equal cruise thrust requirements, cycles of higher specific thrust design have less excessive thrust for low altitude, low Mach number operation. These cycles, therefore, must operate at a higher percentage of maximum available thrust at cutback and approach reference points, thereby yielding higher noise levels, other things being equal.
- Single-Stage Vs. Two-Stage Fan - Due to the basic consideration that the maximum fan noise of a two-stage fan is higher than that of a single-stage fan, systems EPNdB levels are higher for the two-stage fan designs when compared at the same cycle specific thrust. This also holds true for all six categories of estimates and at all three FAR 36 reference points. The difference in EPNdB levels between single- and two-stage fan designs is most pronounced at approach power where the fan noise constituent is most dominant.
- Effectiveness of Suppression Vs. Specific Thrust - For a consistent amount of treatment arrangement (i.e., fully utilizing the space available for a given nacelle), the suppression effectiveness in ΔPNdB generally increases with an increase in cycle specific thrust

- 3-Engine Aircraft
- M = 0.98
- Mixed Exhaust
- TOGW = 193,200 kg (426,000 lbs)
- Hard Surface
- 457 m (1500 ft) Sideline Takeoff

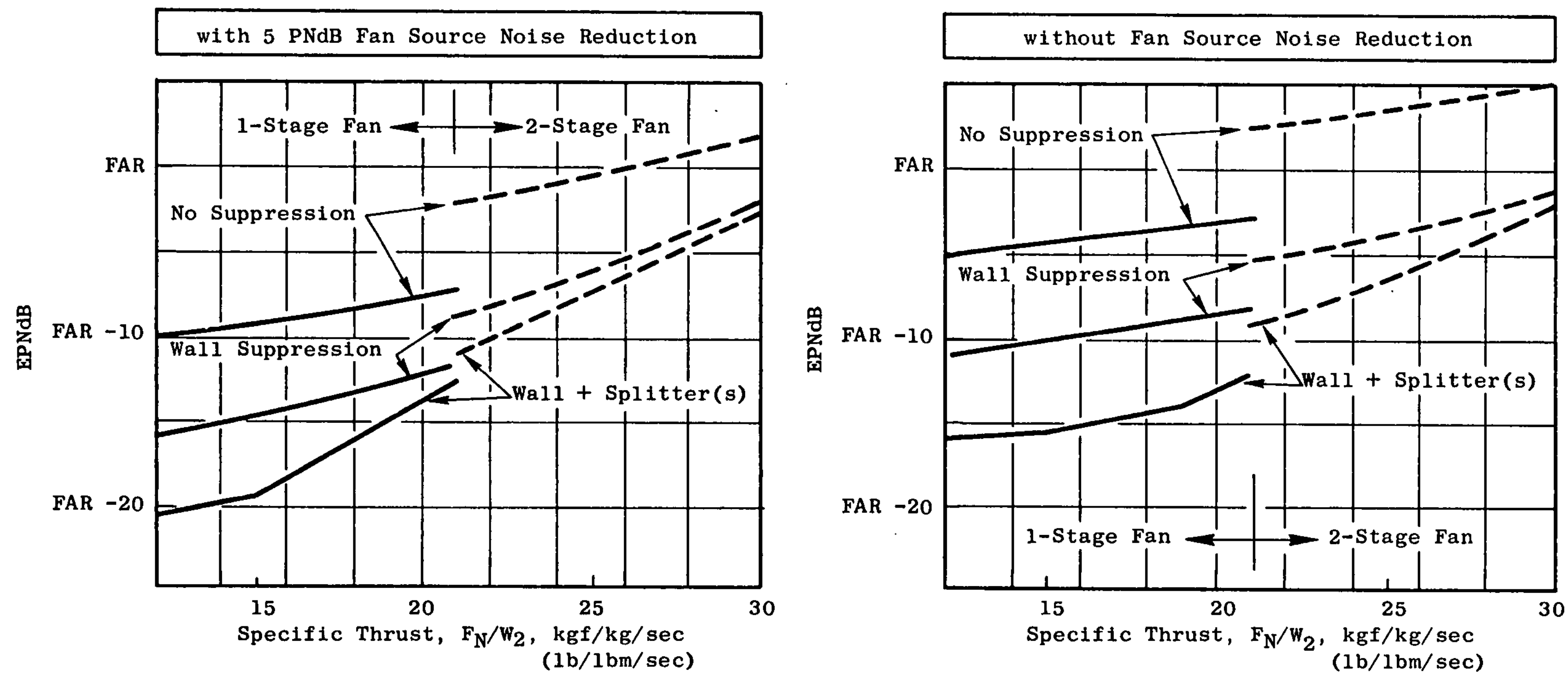
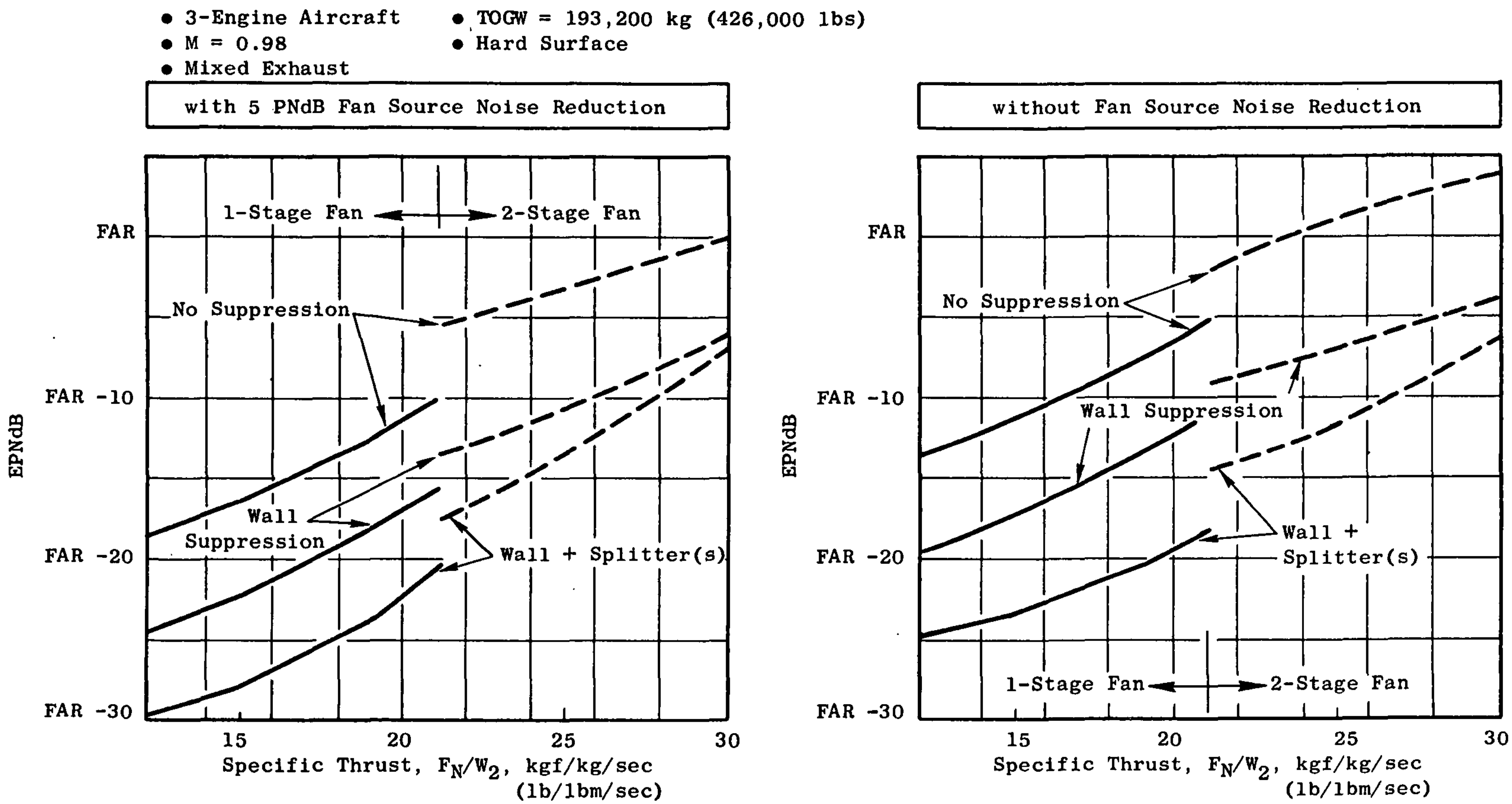
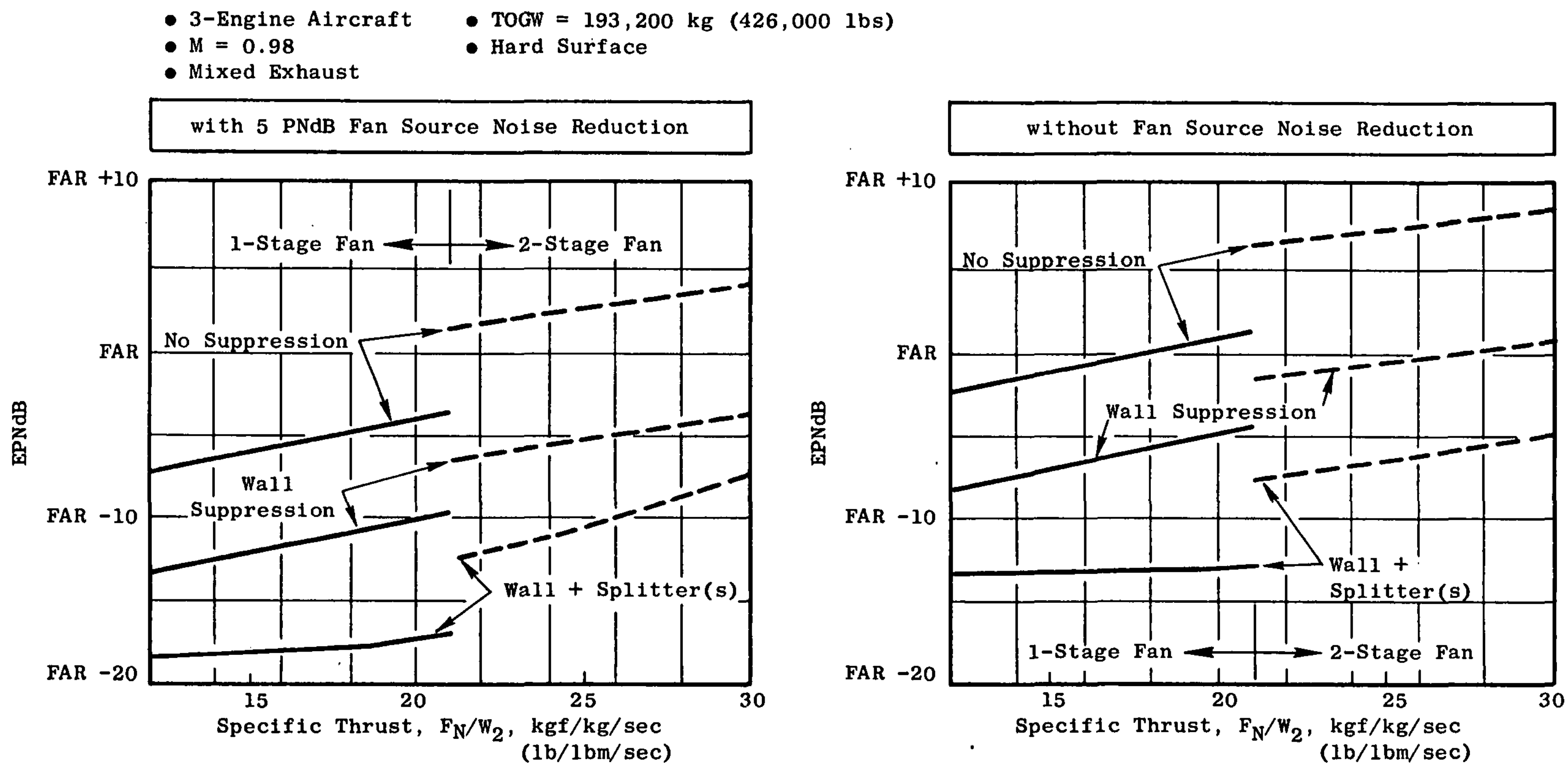


Figure 32. Engine Parametric Study Sideline Noise Estimates as a Function of Specific Thrust (M = 0.98).



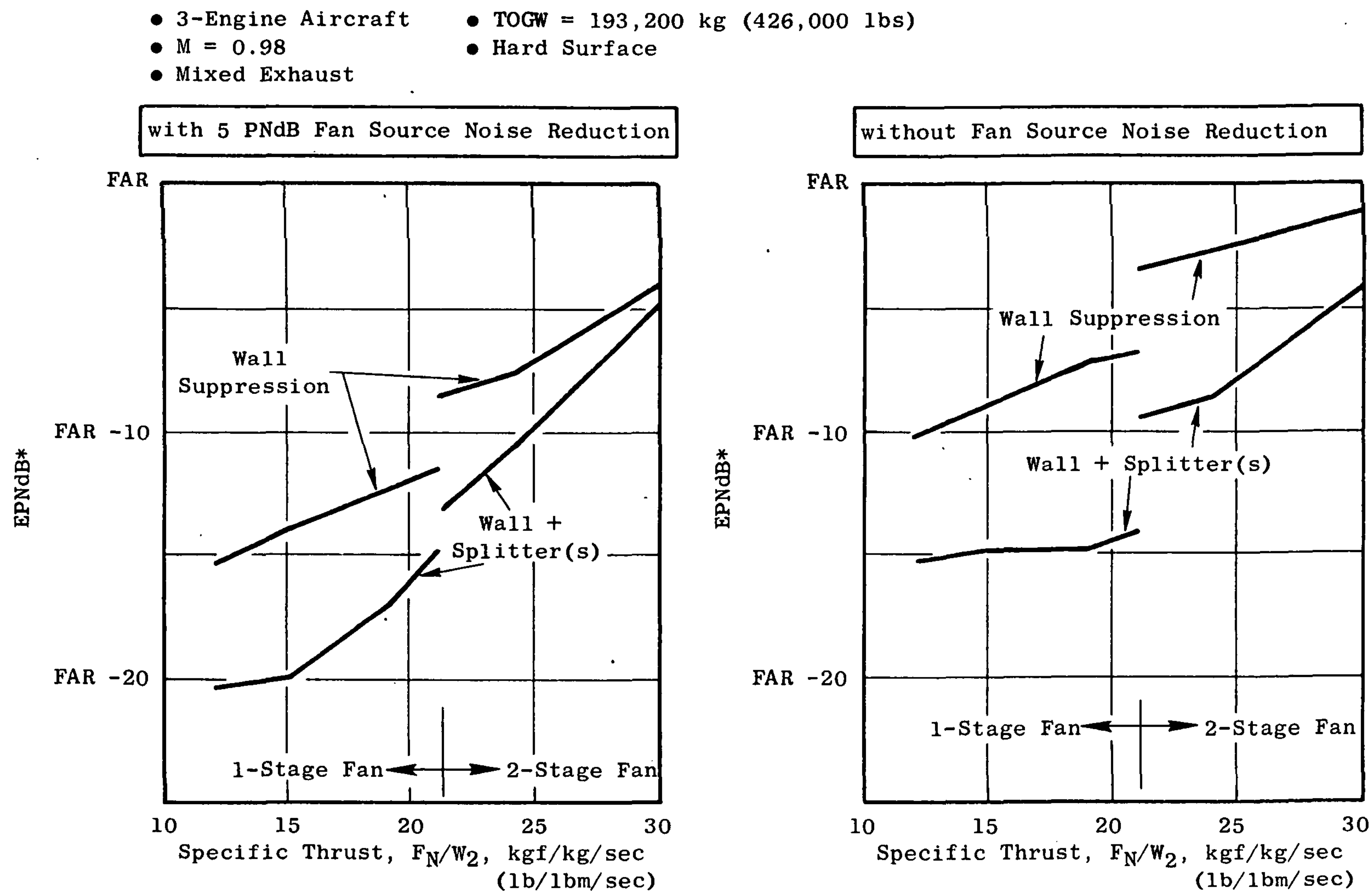
* Refer to measurement point 6482 m (3.5 n mi) from brake release. Estimates made based on power cutback. See Table XIII for altitude and thrust settings for the different study engines.

Figure 33. Engine Parametric Study Community Noise Estimates as a Function of Specific Thrust (M = 0.98)*.



* Refer to measurement point 1852 m (1 n mi) from threshold of landing. See Table XIII for thrust setting for the different engines. Altitude constant at 113 m (370 ft).

Figure 34. Engine Parametric Study Approach Noise Estimates as a Function of Specific Thrust (M = 0.98)*.



* Traded Noise Basis

Figure 35. Engine Parametric Study, Traded Noise Estimates as a Function of Specific Thrust (M = 0.98).

(see Table IX). This results from the fact that the duct passage height generally decreases with lower bypass ratio or higher specific thrust, and that smaller duct height is advantageous toward suppression effectiveness so long as the characteristic blade passing frequency is held nearly constant. With the use of two-stage fans, the fan noise suppression effectiveness is systematically lower, compared to a single-stage fan at the same cycle specific thrust, because the higher blade number used (to reduce chord length and engine length) results in a higher blade passing frequency, thereby leading to a greater passage-height-to-wave-length ratio and poorer suppression effectiveness.

In spite of the generally more favorable suppression effectiveness associated with an increase in cycle specific thrust, the basic trend of higher net noise level with increasing specific thrust, as discussed earlier, still holds true.

- Fan Vs. Jet Noise Constituents - Jet noise PNdB level, in relation to fan PNdB, is most prominent at the maximum power sideline point [457 m (1500 feet)] and in the aft quadrant. It also assumes greater importance in affecting the total systems EPNdB as the fan noise levels are lowered by wall and splitter treatment, and by source reduction on advanced technology engines. Most importantly, since basic jet noise increases faster (9th power approximately) with specific thrust than does fan noise, systems EPNdB levels become more and more influenced or controlled by jet noise at higher specific thrust levels. The crossover points (i.e., Fn/W_2 point beyond which maximum jet noise exceeds maximum fan noise) at the maximum thrust sideline point [457 m (1500 feet)] for several categories of noise estimates are summarized below:

Category	Fn/W_2 Crossover
Wall suppression, advanced technology	20
Full suppression, current technology	18
Full suppression, advanced technology	15

Thus, it is seen that, for ATT engines, jet noise will play an important role in influencing the engine cycle selection to meet the various noise goals.

- Relative Criticality at the Three FAR 36 Points - For specific thrusts less than about 21, the most critical noise condition relative to the noise goals is, in all cases, at approach where fan noise is controlling. Exceeding Fn/W_2 = 21, jet noise becomes more important, and the 457 m (1500 feet) sideline maximum take-off point is most critical.

- FAR 36 Noise Goal - All the studied engines with minimum nacelle wall treatment, with or without advanced technology, can easily meet the FAR 36 requirement at all of the three reference points.

Without the use of wall suppression, single-stage fan engines with a specific thrust less than 20 (even without advanced technology) can meet the FAR 36 requirement on a traded basis.

- FAR 36 - 10 EPNdB Noise Goal - Current technology engines with only nacelle wall suppression cannot meet the FAR 36 - 10 EPNdB noise goal except at the lowest specific thrust considered ($Fn/W_2 = 12$).

  - Current technology two-stage fan engines with specific thrust levels exceeding 20, even with full suppression consisting of two inlet and 1 aft splitters, cannot meet the -10 EPNdB noise goal due to the high fan noise associated with two-stage fan designs.

  - Current technology single-stage fan engines with a specific thrust less than 20 approach FAR 36 - 15 EPNdB with full nacelle suppression (2 inlet and 1 aft splitter). This suggests that a more modest amount of suppression, say a single inlet splitter, may be adequate to meet the FAR 36 - 10 EPNdB goal.

  - Advanced technology single-stage fan engines with specific thrust levels less than 21 and with nacelle wall suppression only can easily meet the FAR 36 - 10 EPNdB goal.

  - Due to the jet noise floor, engines with specific thrust exceeding about 25 cannot meet the FAR 36 - 10 EPNdB goal, regardless of the amount of fan noise suppression applied.

- FAR 36 - 20 EPNdB Noise Goal - Only advanced technology engines with maximum suppression and using a cycle specific thrust (Fn/W_2) less than 15 can meet FAR 36 - 20 EPNdB (traded). All other engines considered in this study failed to meet this goal because of the jet noise floor and too stringent fan noise suppression requirements.

Noise Suppression Penalties

Full inlet and fan duct wall treatment were considered in the basic parametric engine performance, weight, and price. Additional sound treatment penalties due to inlet and exhaust splitters then were assessed separately for each engine beyond the basic wall-treated configuration. Inlet splitters were designed to be anti-iced, and the preliminary weight penalty calculated reflects this requirement. Pressure losses due to the splitters include:

- Splitter surface area skin friction drag

- Splitter profile drag

- Support strut(s) skin friction and profile drag

Penalties charged to the splitters, besides the direct increase in sfc, include the installed weight and price increase incurred as a result of scaling the engine back to the original installed cruise thrust. These effects are added to the weight and cost of the splitters to obtain the total penalties. It was found that approximately half of the aircraft gross weight and economic penalties are due to the weight and price of the splitters themselves and their installation.

The increase in aircraft gross weight, DOC, and ROI for the cycles of most interest are presented in Figure 36. For a consistent treatment definition*, it will be noted that the penalties due to the addition of splitters are highest at the lowest specific thrust, highest bypass ratio cycles (highest treatment areas and lower fan pressure ratio cycle are more sensitive to pressure losses), while noise suppresson effectiveness is the lowest for reasons indicated earlier. The cost per dB of noise suppression therefore is significantly higher for low specific thrust cases.

Economics Versus Noise (Task I)

The direct operating cost penalties versus traded noise for the three-engine Mach 0.98 host aircraft are presented in Figures 37 and 38 for the range of specific thrusts investigated in this study. The only difference between the two figures is the effect of 5 PNdB fan source noise reduction on traded noise assumed in Figure 38.

ΔDOC is shown on a relative basis using the parametric study base case with a specific thrust of 19 and with wall suppression only as the reference point.

The symbols "Ap" and "SL" next to each point indicate whether noise is controlling at approach or sideline, respectively.

The left-hand point of each specific thrust line shows the trend of ΔDOC versus noise with wall suppression treatment only. The right-hand point of each specific thrust line represents the cases with wall treatment plus splitters described earlier. (The dotted line serves only to link the two end points and does not represent the actual rate of change of ΔDOC versus noise; it indicates only the average rate of change.)

From these trends, the following observations can be made:

- Up to a noise goal of approximately 15 EPNdB below FAR 36, the cycle which achieves the best economics without noise constraints also yields the best economics with noise constraints.

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* All cases up to a specific thrust of 24 (inclusive) have 2 inlet and 1 aft splitters. Above a specific thrust of 24, jet noise is too high to benefit from this level of fan noise suppression and only a single inlet splitter and no aft splitter suppression configuration is used to yield a more balanced design.

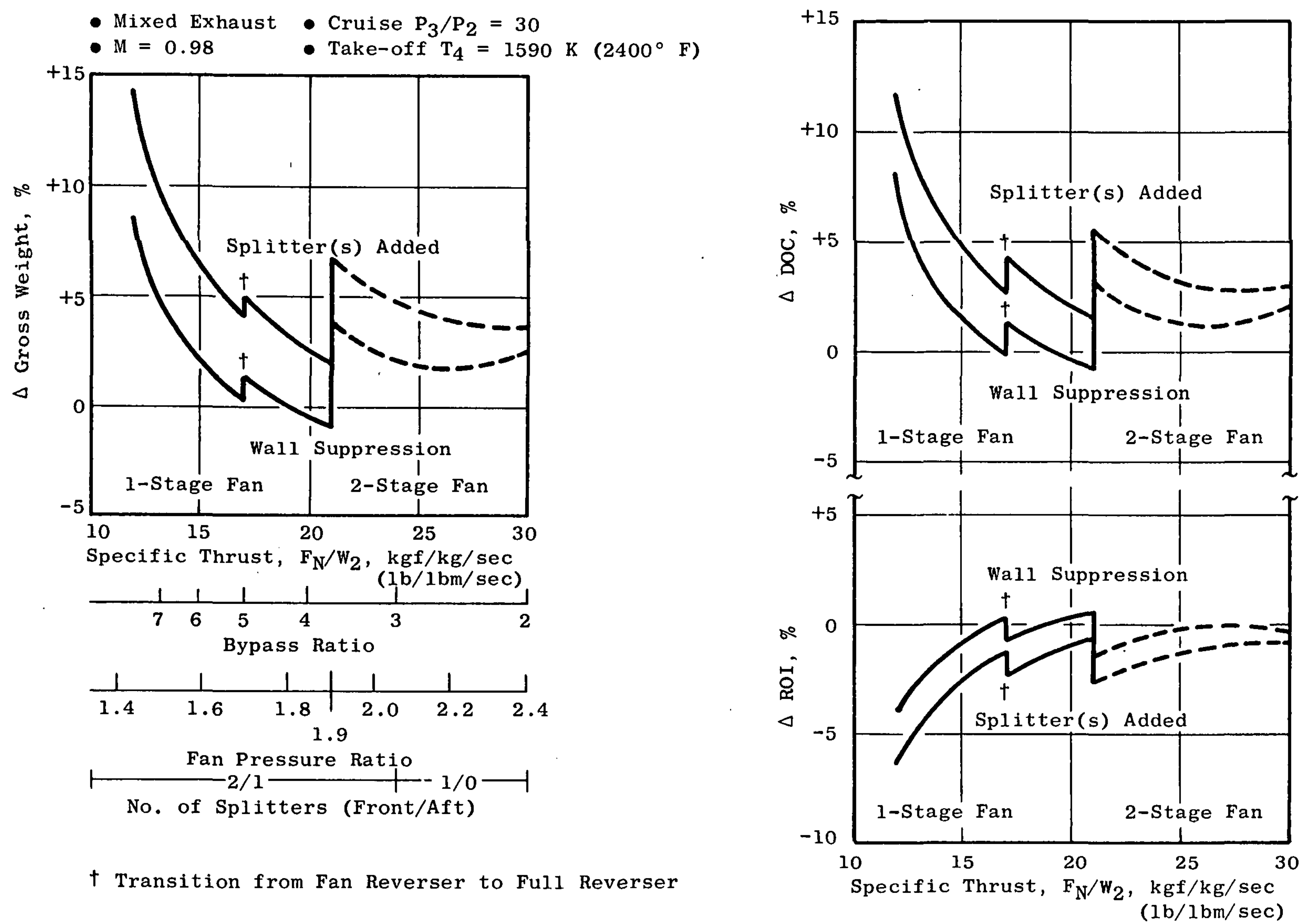


Figure 36. Engine Parametric Study Penalties of Noise Suppression Treatment as a Function of Specific Thrust (M = 0.98).

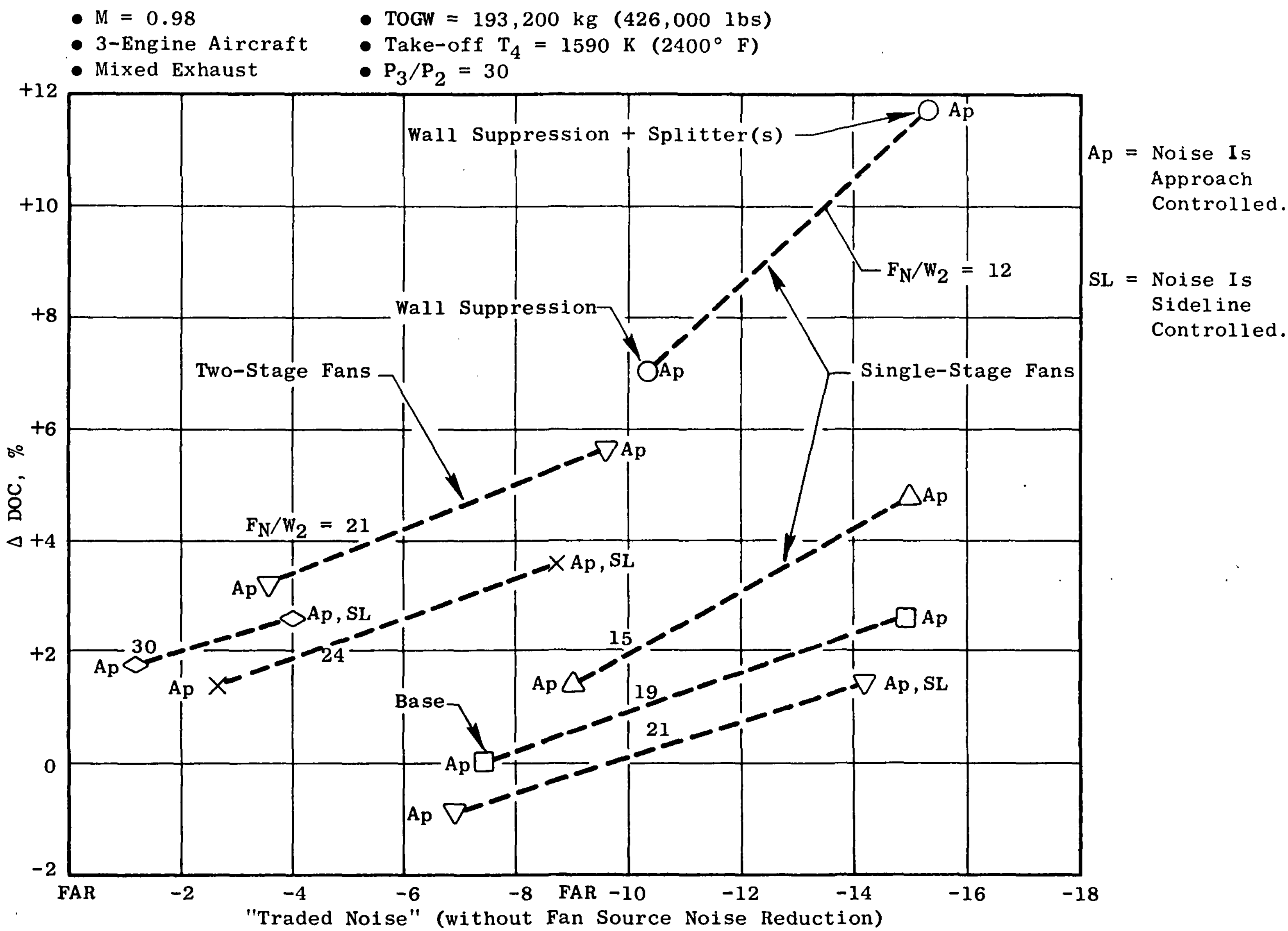


Figure 37. Engine Parametric Study Economic Penalties Versus Traded Noise, without Fan Source Noise Reduction (M = 0.98).

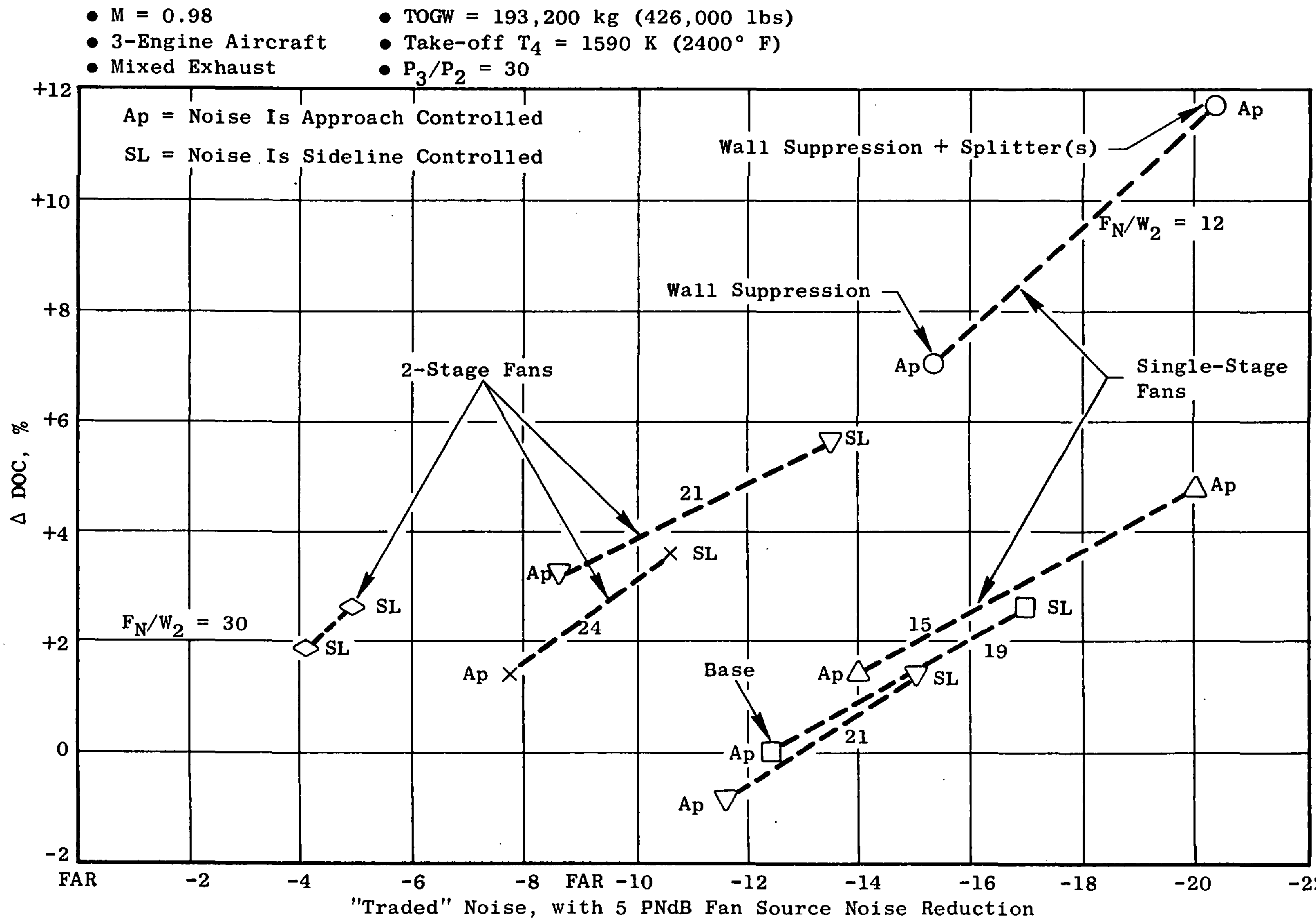


Figure 38. Engine Parametric Study, Economic Penalties Versus Traded Noise, with Fan Source Noise Reduction (M = 0.98).

- For noise goals lower than FAR 36 - 15 EPNdB, sideline jet noise becomes limiting at specific thrusts of 21 and above, and lower specific thrusts must be selected; without fan source noise reduction, more noise suppression treatment than used in the study must be applied to realize these lower noise goals.

- In any situation encountered, for any noise level, the highest specific thrust cycle with a single-stage fan that can meet that noise level yields the best economics. Two-stage fan systems are shown to have both poorer economics and higher noise.

- A noise level of FAR 36 - 10 EPNdB appears achievable with relatively small economic penalty without fan source noise reduction.

- A noise level of FAR 36 - 15 EPNdB also appears achievable without fan source noise reduction, but requires more suppression and involves a greater economic penalty.

- A noise level of FAR 36 - 20 EPNdB also could be achieved without fan source noise reduction with a specific thrust of 15 or less, but would require much more suppression treatment than applied and would result in very severe economic penalties. If fan source noise could be reduced by 5 PNdB, the economic penalties would be decreased considerably, as indicated by comparing Figures 37 and 38.

It should be noted that the penalties and noise differences shown for additional noise suppression treatment are applicable to other combinations of T_4 and cycle pressure ratio without any significant error.

For separate exhaust configurations, the same general trends prevail. At a given specific thrust, for the energy extraction assumed, the jet noise would be about the same as for the mixed exhaust; the fan noise would be somewhat higher because of the higher fan pressure ratio and tip speed required by the cycle; and, therefore, slightly more suppression treatment would be needed to achieve the same fan and overall noise level as the mixed exhaust cycle at the same specific thrust. The net effect would be to reflect slightly higher DOC penalties to achieve a given noise level, in addition to the penalties associated with the cycle effects indicated earlier.

Penalty Estimates for NO_x Control

To meet the NO_x emission objectives of 3 g NO per kg fuel, combustor water injection is required. The estimated take-off gross weight penalty due to the addition of a water injection system is presented in Table XIV for two cycles of interest. It is assumed that all the water is consumed at takeoff, and, therefore, no water is carried onboard during the remainder of the mission. These estimates were refined during the Task II preliminary design effort for the specific engines studied with take-off gross weight penalties of about one half those indicated here.

TABLE XIV. PENALTY ESTIMATES FOR NO_x CONTROL, TASK I.

	1590 K (2400° F)	1920 K (3000° F)
• Cycle - Take-off T_4 [Std Day +14° C (+25° F)]	1590 K (2400° F)	1920 K (3000° F)
- Cruise Pressure Ratio	30	40
• H_2O Required with Advanced Carbureting Combustor for 3 g NO/kg Fuel, % Combustor Flow	$2\frac{1}{2}$ to $3\frac{1}{2}$%	3 to 4%
• Combustor Flow for F_N/W_2 = 19 Cycle, per Engine Sized to Power M = 0.98 Aircraft, at TOGW = 193,200 kg (426,000 lbs)	97 kg/sec (213 lbs/sec)	65 kg/sec (143 lbs/sec)
• Water Required for 90 sec at Takeoff, per Engine [Estimated Time to Reach 6482 m (3.5 n mi) Point].	218 to 304 kg (480 to 670 lbs)	177 to 236 kg (390 to 520 lbs)
• Estimated Weight Penalty per Engine for Water Injection Capability	86 to 113 kg (190 to 250 lbs)	73 to 95 kg (160 to 210 lbs)
• Estimated Effect on TOGW Due to H_2O Injection	+0.5 to +0.7%	+0.4 to +0.6%

CONCLUSIONS AND RECOMMENDATIONS - TASK I

Conclusions

For the 5556 km (3000 nautical mile) range, high performance airplanes studied, the significant results and conclusions reached in Task I are summarized below:

- For a Mach 0.98 aircraft, the highest specific thrust engine (lowest bypass ratio for a given core technology) obtainable with a single-stage fan (assumed to be limited to 1.9 pressure ratio) yielded the best mission performance.

- The above conclusion applies for noise levels down to 15 EPNdB below FAR 36. Sideline jet noise becomes limiting for any lower level of engine noise.

- For a Mach 0.90 aircraft, the high specific thrust engine with a single-stage fan also yielded good economics, but a somewhat lower specific thrust engine also was competitive.

- The single-stage fan engine was lighter and less expensive than a two-stage fan in the specific thrust range where both could be considered. The two-stage fan was assessed as having a higher noise for a one-chord spacing, based on limited experimental data. The single-stage approach therefore was recommended for Task II.

- A mixed exhaust configuration showed a significant advantage in mission performance over a separate exhaust configuration. In addition to the propulsive efficiency advantage, it allowed a higher specific thrust cycle to be utilized within the pressure ratio limitation of a single-stage fan. The mixed flow approach therefore was recommended for Task II.

- A mixed-exhaust configuration showed a significant advantage in mission performance over a single-exhaust configuration. In addition to the propulsive efficiency advantage, it allowed a higher specific thrust cycle to be utilized within the pressure ratio limitation of a single-stage fan. The mixed-flow approach therefore was recommended for Task II.

- Advanced core technology [1920° K (3000° F) turbine temperature and 35-40 cycle pressure ratio] can provide a significant improvement in mission performance based on projected cooling and materials development.

Recommendations (at end of Task I)*

Continue the planned Task II preliminary design effort for a Mach 0.95 - 0.98 application based on the following mixed exhaust engine cycles:

Approximate certification date	Mid to late 70's	Early 80's
Specific thrust at cruise, kgf/kg/sec (lb/lbm/sec)	20.5	20.5
Fan pressure ratio	1.87	1.9
Bypass ratio	4.2	5.5
Turbine inlet temperature		
- Takeoff, ° K (° F)	1645 (2500)	1920 (3000)
- Cruise, ° K (° F)	1589 (2390)	1864 (2890)
Cycle pressure ratio at cruise	30	35 - 40
Fan design	1 stage	1 stage
Fan tip speed, m/sec (ft/sec)	490-50 (1600-1659)	490-550 (1600-1800)
Composites	Fan blade(1)	Fan blade, frame & boosters
Acoustic treatment	Wall	Wall
Noise level	FAR 36 - 10 EPNdB	FAR 36 - 10 EPNdB
Emission control	Water injection, high idle efficiency	Water injection, high idle efficiency

* Note - As Task II progressed, various changes were made; see Task II Section.

(1) Changed to tip-shrouded titanium in Task II.

TASK II - ENGINE PRELIMINARY DESIGNS

INTRODUCTION

Based on the results of the Task I parametric studies, two engine cycles were selected for preliminary engine design studies. These cycles are essentially those recommended at the conclusion of Task I, with the following modifications to reflect NASA-Lewis redirection:

1) More definitive time frames were specified for each engine by the NASA ATT Project Manager as follows:

Engine Designation	Commercial Certification Date
ATT No. 1	1979
ATT No. 2	1985 (or beyond)

2) Noise objectives for the later time period engine (ATT No. 2) were changed from 10 EPNdB below FAR Part 36 to 15 EPNdB below FAR Part 36, with a goal of 20 EPNdB below FAR Part 36, utilizing technology advances and novel flight operating procedures. A noise objective of 10 EPNdB below FAR Part 36 for the near-term engine was retained.

3) Engine cruise specific thrust was decreased slightly from 20.5 to 19.8 to better accommodate the range of cruise design speeds (Mach 0.90 to 0.98) specified, with a minimum amount of compromise.

4) Engine ratings were modified to better satisfy the aircraft requirements for a three-engine (two underwing and one tail) aircraft design for a 18,140 kg (40,000 lb) passenger payload and a 5556 km (3000 nautical mile) range. Both engines have a single-stage fan and a mixed-flow exhaust configuration. The distinguishing difference between the two engines is that of technology level. The near-term engine utilizes a level of technology compatible with a certification date of 1979. The primary objective of this design study was to provide a sound base for the ATT aircraft contractors' airplane studies. The later-term engine utilizes a projected level of technology compatible with a commercial certification date of 1985. Here, the emphasis was placed on advanced technology features for improved emissions, aircraft performance, and flight safety. Noise and emission study objectives are shown in Table XV and an overall engine design summary is presented in Table XVI. Note that this is for the engine size in which the study was conducted. Appropriate scale factors were provided to the ATT airframe study contractors to cover their particular engine size requirements. The engine take-off thrust required for the Mach 0.98, three-engine airplane described above is approximately 155 kN (35,000 lbs) at sea level static. The general engine layouts are shown schematically to the same scale in Figures 1 and 2.

TABLE XV. NOISE AND EXHAUST EMISSIONS OBJECTIVES FOR TASK II.

Parameter	Engine Designation	
	ATT No. 1	ATT No. 2
Noise Objectives Relative to FAR Part 36	-10 EPNdB†	-15 EPNdB† (-20 EPNdB goal with technology advances and flight operating procedures)
Exhaust Emissions Objectives Pollutant:		
• CO at Idle	40 g/kg Fuel	Same
• Unburned H/C's at Idle	8 g/kg Fuel	Same
• NO at Takeoff	3 g/kg Fuel	Same
• Smoke at Takeoff	SAE No. 15‡	Same

† For M = 0.95 to 0.98 trijet with 18,150 kg (40,000 lb) payload, 5556 km (3000 n mi) range.

‡ Using SAE ARP 1179 measurement specification.

TABLE XVI. BASIC ENGINE SUMMARY, TASK II.

Parameter	Engine Designation	
	ATT No. 1	ATT No. 2
CYCLE		
• Fan Pressure Ratio	1.83	1.85
• Bypass Ratio	4.1	5.6
• Overall Pressure Ratio	30	37.2
• Turbine Rotor Inlet Temperature (Hot Day Takeoff)	1645 K (2500° F)	1920 K (3000° F)
PERFORMANCE (Uninstalled)		
• Design Corrected Airflow	642 kg/sec (1415 lbm/sec)	642 kg/sec (1415 lbm/sec)
• Rated Take-off Thrust [Flat Rated to Standard +17.2° C Day (+31° F)]	209 kN (47,000 lbs)	209 kN (47,000 lbs) (Dry) 222 kN (50,000 lbs) (with Water)
• M = 0.96, 11,280 m (37,000 ft), Maximum Cruise Fn, to Standard +10° C Day	53 kN (11,900 lbs)	53 kN (11,900 lbs)
sfc, Standard Day	0.696 kg/kgf-hr	0.681 kg/kgf-hr
WEIGHT		
• Basic Engine Weight	3670 kg (8100 lbs)	3220 kg to 2490 kg (7100 to 5500 lbs)
• Thrust/Weight at Takeoff	5.8 kgf/kg	6.6 to 8.5 kgf/kg
DIMENSIONS		
• Fan Tip Diameter	25.66 m (84.2 in.)	24.87 m (81.6 in.)
• Length, Flange to Flange	38.56 m (126.5 in.)	29.57 m (97 in.)

ENGINE DESCRIPTION

Cycle and Performance

The engine cycles (Table XVII) reflect the higher core technology level selected for ATT No. 2 (higher T_4 and cycle pressure ratio). Note that the higher bypass ratio of engine No. 2, which results from the smaller core size now possible with the higher specific core energy available, does not imply a higher propulsive efficiency which has purposely been held constant by selecting the same value of engine specific thrust (Fn/W_2). The benefits of higher core technology then will be reflected in a smaller core and lower engine weight and a higher thermal efficiency (lower). Both engines have their components matched at their respective aerodynamic design points at cruise. The engine ratings shown in Table XVIII provide the proper thrust relationship between takeoff and cruise for the host airplanes of interest. Maximum climb for engine No. 2 is derated by about 5% at sea level on hot days to maintain the compressor exit temperature within design limits. The full maximum climb rating is restored above 1980 m (6500 feet), with the amount of cutback varying linearly between these two altitudes. Compressor exit temperature at takeoff on hot days is controlled by a small amount ($\sim$ 1/2%) of compressor inlet water injection which is used in any case for NO_x control in the combustor.

Performance at cruise and takeoff is compared in Table XIX with the effects of installation losses indicated. Because both engines have the same specific thrust and temperature rating relationships, their cruise-to-take-off thrust lapse rate is also the same.

Component Aerodynamic Design Summary

Table XX compares the major aerodynamic characteristics of each component. Both single-stage fans are tip shrouded with engine No. 2 having a fan blade aspect ratio in the order of 20% higher than the near-term engine. The combination of higher specific flow and lower fan inlet radius ratio results in approximately 7% higher flow per unit frontal area for engine No. 2, which can be reflected in a smaller nacelle diameter. Both fans are designed to the same stall margin.

A higher core supercharging pressure ratio is achieved for ATT No. 2 with the same number of booster stages, comparable aerodynamic loading, and the same stall margin because of the higher average wheel speed available and the use of casing treatment in the booster stages.

The core components for engine No. 1 are based on components currently under development. Engine No. 2 core components project advances in one or more areas, relative to engine No. 1.

The increased core compressor pressure ratio for engine No. 2 with the same objective stall margin is obtained with one less stage by a combination of higher tip speeds, higher loadings, and the use of casing treatment.

TABLE XVII. CYCLE, TASK II.

- 12,192 m (40,000 ft)
- Mach No. = 0.96
- Maximum Cruise

Parameter	Engine Designation	
	ATT No. 1	ATT No. 2
Overall Pressure Ratio	30.0	37.2
Turbine Rotor Inlet Temperature, Standard +10° C Day	1545 K (2320° F)	1820 K (2820° F)
Bypass Ratio	4.1	5.6
Fan Pressure Ratio	1.83	1.85
Fan Corrected Flow $(W\sqrt{\theta}/\delta)_2$	642 kg/sec (1415 lb/sec)	642 kg/sec (1415 lb/sec)
Specific Thrust, F_N/W_2	19.8 kgf/kg/sec	19.8 kgf/kg/sec

TABLE XVIII. ENGINE RATINGS, TASK II.

Condition	T_4, Hot Day	
	ATT No. 1	ATT No. 2
TAKEOFF (Standard +17.2° C Day (Standard +31° F Day)	1645 K (2500° F)	1920 K (3000° F)
MAXIMUM CLIMB (Standard +10° C Day)	1600 K (2420° F)	1850† to 1880 K (2870°† to 2920° F)
MAXIMUM CRUISE (Standard +10° C Day)	1545 K (2320° F)	1820 K (2820° F)

† Maximum climb is derated between sea level and 1980 m (6500 ft) to maintain compressor exit temperature within design limits on hot days.

TABLE XIX. PERFORMANCE, TASK II.

Parameter	Δ sfc	Engine Designation: ATT No. 1	Engine Designation: ATT No. 2
A. 12,192 m (40,000 ft), Mach No. = 0.96, Maximum Cruise			
• Thrust			
• Installed †		43 kN (9650 lbs)	43 kN (9650 lbs)
• Bare Engine		46 kN (10,300 lbs)	46 kN (10,300 lbs)
• Δ Fn Bare-Installed		+6.8%	+6.8%
• sfc, Standard Day			
• Installed †	-2.5%	0.716	0.698
• Bare Engine	-2.2%	0.696	0.681
B. Takeoff, Sea Level, M = 0			
• Thrust			
• Installed ‡		189 kN (42,600 lbs)	189 kN (42,600 lbs)
• Bare Engine		209 kN (47,000 lbs)	209 kN (47,000 lbs)
• Δ Fn Bare-Installed		+11%	+11%
c. Thrust Lapse Rate: $\frac{\text{Fn Maximum Cruise, 12,192 m (40,000 feet), M = 0.96}}{\text{Fn Takeoff, Sea Level, M = 0}}$			
• Installed		0.226	0.226
• Bare Engine		0.220	0.220

† η_R = 0.994, 0.91 kg/sec (2 lb/sec) Interstage Bleed, 74.6 kW (100 hp) Extraction.

‡ η_R = 0.960, 0.91 kg/sec (2 lb/sec) Interstage Bleed, 74.6 kW (100 hp) Extraction.

TABLE XX. COMPONENT AERODYNAMIC DESIGN SUMMARY, TASK II.

Parameter	Engine Designation	
	ATT No. 1	ATT No. 2
• Fan, Single-Stage		
• Corrected Tip Speed	503 m/sec (1650 ft/sec)	533 m/sec (1750 ft/sec)
• Fan Pressure Ratio	1.83	1.85
• Corrected Flow/Annulus Area	205 $kg/sec/m^2$ (42 $lbs/sec/ft^2$)	215 $kg/sec/m^2$ (44 $lbs/sec/ft^2$)
• Radius Ratio	0.36	0.34
• Type Shrouds	Tip	Tip
• Boosters		
• Number of Stages	2	2
• Supercharging P/P (Including Fan Hub)	2.5	2.7
• Core Compressor		
• Number of Stages	9	8
• Pressure Ratio	12	14
• Corrected Tip Speed	410 m/sec (1345 ft/sec)	462 m/sec (1515 ft/sec)
• Corrected Flow	59 kg/sec (130 lbs/sec)	43 kg/sec (95.5 lbs/sec)
• Combustor		
• Type	Carbureting	Double-Annular Carbureting
• Idle Emissions Feature	CDP Bleed	Shut-off Inner Annulus
• NO_x Emissions Feature	H_2O Injection	H_2O Injection
• Core Turbine (Single-Stage)		
• Pressure Ratio	4.06	3.95
• Δh	469,800 J/kg (202 Btu/lb)	541,900 J/kg (233 Btu/lb)
• Maximum Tip Speed	579 m/sec (1900 ft/sec)	610 m/sec (2000 ft/sec)
• Pitch Work Coefficient, $gJ\Delta h/U_p^2$	1.7	1.9
• Fan Turbine		
• Number of Stages	3	4
• Pitch Work Coefficient, $gJ\Delta h/U_p^2$	2.2	2.4
• Mixer		
• Type	Partial	Partial or Injection
• Effectiveness	60%	60%

Both combustors are carbureting designs with provisions for maintaining relatively high fuel/air ratios at low power levels to retain high combustion efficiency, thereby achieving low idle emissions. Engine No. 1 controls the fuel/air ratio by bleeding approximately 15% of compressor discharge air at idle; engine No. 2 shuts off the fuel to the inner annulus of the double-annular design to accomplish the same objective in a more sophisticated and controlled manner. Although carbureting combustion systems offer a significant improvement in reducing the amount of NO_x emissions (Figure 16) compared to current technology systems, it is necessary to use combustor water injection to meet the study objective levels shown in Table XV.

Trade studies performed under other programs have shown a single-stage core turbine to be superior to a two-stage design for the same task. Significantly lower cooling and leakage air, fewer parts, shorter length, and lower cost of the single-stage design more than compensate for its lower efficiency. A deliberate choice therefore was made to select cycles and turbomachinery arrangements that would permit the use of a single-stage core turbine for both engines.

Both low pressure turbines are close coupled to the high pressure turbine, and neither engine requires an interturbine frame. Due to the significantly lower core flow of engine No. 2, the low pressure turbine requires an additional stage and an average loading which is moderately higher than that of engine No. 1. Both low pressure turbines have a lightly loaded last stage to minimize exit swirl.

The exhaust multilobe mixer selected for engine No. 1 is based on experimental scale model test results obtained for several configurations.

Turbine Cooling Design Considerations

The parametric study conducted in Task I identified major gains in mission performance and economics with higher temperature cycles, such as that selected for engine No. 2, provided that cooling and other parasitic flows could be minimized. In this study, advanced cooling technology projections were made based on current research and development work being conducted at General Electric at turbine inlet temperature levels of engine No. 2 and beyond.

As mentioned previously, the use of a single-stage turbine is very effective in minimizing the chargeable cooling air as temperature increases because of its high work extraction and, therefore, the high temperature drop which takes place in one stage. Besides the improvements in basic cooling technology which deal with the fundamental heat transfer mechanism (convection, impingement, film, full coverage film, transpiration), other factors play a significant part in minimizing the cooling air requirements. These include the following:

1) Higher temperature blade materials

2) Higher temperature coatings

3) Blade and vane temperature gradients

4) Cooling air temperature

5) Method of taking cooling air on board the wheel

Higher temperature blade and coating materials expected to be developed in time for use in engine No. 2 were used. Lower blade and vane temperature gradients also were used, based on anticipated improvements in cooling air management. These could be applied to advanced film plus impingement cooled blades under development or to new, full coverage film, laser-drilled blades. The result of all of the above effects is a relatively small increase in cooling air for engine No. 2, relative to No. 1, for a 278° K (500° F) increase in turbine inlet temperature.

For the fan turbine, only the first stator vanes of engine No. 1 are cooled. The first three blade rows of the fan turbine for ATT No. 2 require cooling. There is, therefore, a significant increase in cooling air required for engine No. 2, but all the cooling air used for the low pressure system is extracted at an intermediate compressor stage and is, therefore, less costly to the cycle.

Controls

The fuel and control systems contemplated for both ATT engines No. 1 and No. 2 incorporate similar advanced control and engine power management concepts which are believed desirable for the next generation of commercial transports. As shown in Table XX1, the fuel control objectives emphasize reduced pilot workload, which can be achieved by providing the automatic features listed, and the ability of the control to interface with the aircraft power management system for the purpose of providing engine trimming, fault isolation, and engine trend monitoring. To this end, both systems incorporate electrical computation. Analog electronics are envisioned for the near-term engine, since the development of large scale integrated circuits required for the digital controls proposed for engine No. 2 probably would not be completed in time. Digital electronics proposed for ATT No. 2 have several potential advantages:

- They are cheaper in large production quantities
- They are more reliable (through self-test and redundancy)
- They can interface more easily with aircraft systems
- Trend monitoring and fault isolation eventually could be accommodated in the computer

Table XXII briefly describes the functions of the control system. Fan corrected speed would be the primary governor demand, since it is closely related to engine thrust output and ties in conveniently with automatic engine flat rating and lapse rate control functions. An electrical core

TABLE XXI. CONTROL SYSTEM DESIGN OBJECTIVES.

ATT No. 1 and ATT No. 2
• Provide Automatic Flat Rating and Lapse Rate Control.
• Provide Automatic T_4 Limiting.
• Provide Automatic Speed Limiting (N_1, N_2, $N_1/\sqrt{\theta_2}$, $N_2/\sqrt{\theta_{2C}}$).
• Simplify Pilot Workload.
• Compatible with Airframe Power Management System.
• Provide a Simple, Reliable Control System.
• Provide a Lightweight, Fire-Safe Fuel System.
Note: N_1 = Fan rpm; N_2 = Core rpm

TABLE XXII. CONTROL SYSTEM FUNCTIONS.

ATT No. 1 and ATT No. 2
• Controls Thrust as a Function of Power Lever Angle while Limiting Maximum Speeds, Temperature, and Compressor Discharge Pressure.
• Maintains Stall Margin and Prevents Overtemperature During Rapid Throttle Movements.
• Incorporates a Redundant Electrical Backup Governor.
• Schedules Stators and Bypass Doors.
• Schedules Items for Emissions Control, Idle and Takeoff.

speed governor would provide a backup system in case of a failure in the primary system to automatically limit engine thrust loss. More direct temperature limiting of the high pressure turbine blades is planned by means of an optical pyrometer whose output signal is fed to the control. The control also provides the additional necessary functions for the control of emissions, as follows:

At idle:

For ATT No. 1 - opens compressor exit bleed valve

For ATT No. 2 - shuts off fuel to the inner annulus of the double annular combustor

At takeoff:

Provides water injection control to the combustor and, for ATT No. 2, the compressor inlet, as well, for the control of compressor exit temperature.

The control features that can be provided for an advanced transport engine are compared in Table XXIII with those of one of the latest commercial transport engines, the General Electric CF6, which powers the McDonnell-Douglas DC-10. It puts in perspective the advantages that can be realized with the advanced control system contemplated for ATT.

Mechanical Design Features and Weight

The preliminary design of the near-term engine (ATT No. 1)* builds upon advanced technology components and other technology features which are currently under development (scaled and modified as needed) to provide a sound design, capable of being commercially certified in the late 1970's. Table XXIV summarizes the major features of the basic engine. Composite fan blading was considered but rejected for this time period. The fan is tip shrouded, of solid titanium construction, and uses Ti 17 for increased strength. It is based on previous fans of similar design. The core engine is based on advanced designs under development with turbine temperatures approaching the ATT No. 1 level.

Maintainability features were considered throughout the design effort and incorporated in the engine wherever possible. Such features include, for example, the capability to remove the fan as a complete unit from the front without breaking the sump, and a mounting system which permits either top or side mounting of the engine to accommodate the different aircraft installations.

A weight breakdown of the major components (Table XXV) also is presented as a percent of the total basic engine weight for major functional groupings. It shows that the low pressure system makes up nearly 50% of the basic engine weight with the core representing 32% of the weight. The single components

* See Figure 1 for general arrangement.

C. 2

TABLE XXIII. CONTROL MODE COMPARISON.

CF6	ATT No. 1 and ATT No. 2
1. N_2 Governor	$N_1/\sqrt{\theta_2}$ Governor with $N_2/\sqrt{\theta_{2C}}$ Backup
2. Hydromechanical Fuel Control and Computations	Hydromechanical Fuel Control and Electrical Computation
3. Manual Temperature Limiting	Automatic Temperature Limiting
4. Manual N_1 Limiting	Automatic N_1 and N_2 Limiting
5. Manual Flat Rating	Constant P_2 Flat Rating
6. No Lapse Rate Control	$N_1/\sqrt{\theta_2}$ Provides Automatic Lapse Rate Control
7. Acceleration Schedule, $W_F/P_{S3} = f\ (N_2,\ T_{2C})$	Same
8. Variable Stator Vanes Position = $f\ (N_2/\sqrt{\theta_{2C}})$	Same
9. CF6-50 Variable Booster Bleed Valve Position = $f\ (N_2/\sqrt{\theta_{2C}})$ + Bleed Valve Kicker for Acceleration.	Variable Booster Bleed Valve Position = $f\ (N_1/\sqrt{\theta_{2C}},\ N_2/\sqrt{\theta_{2C}})$
Note: N_1 = Fan rpm; N_2 = Core rpm	

TABLE XXIV. ATT No. 1 DESIGN FEATURES, BASIC ENGINE.

1. Tip-Shrouded Ti Fan
2. CF6-50 Type Booster Arrangement
3. Scaled Advanced Technology Core
   - Scaled Compressor
   - Combustor Designed for 1645 K (2500° F)
   - Turbine Designed for 1645 K (2500° F)
4. Advanced Materials Consistent with Late 1970's
5. Control and Accessory Features for Late 1970's

TABLE XXV. ATT No. 1 BASIC ENGINE WEIGHT BREAKDOWN.

Item	Kilograms	Pounds	% Total
Fan Rotor and Low Pressure Shaft	472	1040	---
Fan Stator and Casing and Guard	313	690	---
Boosters	211	465	---
Fan Frame	297	655	---
Subtotal	1293	2850	34
High Pressure Compressor	438	965	---
Combustor and Casing	225	495	---
High Pressure Turbine	517	1140	---
Subtotal	1179	2600	32
Low Pressure Turbine	381	840	---
Rear Frame	141	310	---
Subtotal	522	1150	15
Drives and Sumps	132	290	---
Controls and Accessories and Configuration	308	680	---
Subtotal	440	970	12
Bare Weight	3434	7570	---
Margin	240	530	7
Total Weight	3674	8100	100
Thrust = 209 kN (47,000 lbs)			
Thrust/Weight = 5.8 kgf/kg (5.8 lb/lbm)			

which would benefit most from the application of advanced technology are the fan rotor and the high pressure turbine, the two heaviest items. The bare engine thrust-to-weight ratio for engine No. 1 is 5.8 in this thrust size. This is approximately 20% higher than the latest engines flying today in commercial service, when compared at the same thrust.

The mixer weight is included in the installation weights shown in Table XXVl. The fan inlet, fan cowl, and exhaust nozzle plug weights include wall sound treatment material which is assumed fully integrated with these structures. Otherwise, conventional materials and designs have been used to estimate cowl weights. The installation items as a group represent a large percentage (46%) of the basic engine weight and, as such, identify major areas where future applied efforts to reduce weight may prove well worthwhile.

The design objectives of engine No. 2 stressed the integration of advanced mechanical design features and materials with the higher technology cycle and air design to achieve a low weight, compact design with special consideration given to safety concepts. The advanced features listed in Table XXVII are either novel or are based on technology projections judged to be compatible with the 1985 time period. Particularly noteworthy are the tip-shrouded, short-chord fan blade utilizing low density material; the fail safe design approach used for the fan and core turbine discs which involve multiple disc construction; the composite fan frame struts requiring development to successfully integrate with a metal structure for attachment to mating parts; and the laser-drilled, full coverage film turbine blades. All these require further design study and much development, but are felt to be worthy of consideration. The weight reduction in functional groups projected for engine No. 2 relative to engine No. 1 is shown as a range in Table XXVIII. This range depends on the extent to which the very advanced features proposed for ATT No. 2 can be implemented successfully. The smaller weight reduction assumes mechanical design and materials technology similar to ATT No. 1 and the higher weight reduction assumes success in the implementation of the advanced design concepts considered for ATT No. 2.

Installation

The pod configurations were evolved using the approach outlined in Task I and by continued consultation with the ATT airframe study contractors. The nacelles for this high subsonic application are characterized by high fineness ratio, gentle wall curvature, and low boattail angles. Figure 39 provides a summary of the nacelle and inlet dimensions. The Mach 0.98 designs have a thin-lip, low-contraction-ratio inlet for good cruise performance which requires blow-in-doors (BID) or a viable variable geometry scheme for satisfactory low speed recovery at takeoff. The Mach 0.90 design has a more conventional, fixed geometry, higher-contraction-ratio inlet which provides good cruise and take-off performance. All inlets are longer than would be dictated by good internal diffusion criteria to accommodate inlet noise suppression treatment requirements. All engines are relatively tightly cowled ($D_{HL}/D_{max.}$ = 0.88), but provide adequate clearance over the fan tip for structure and all necessary servicing. To capitalize on the smaller fan tip diameter of engine No. 2, a higher maximum inlet throat Mach number was used

TABLE XXVI. ATT No. 1 INSTALLATION WEIGHT.

Item	Kilograms	Pounds
Fan Inlet	424	935
Fan Cowl	288	635
Fan Exhaust	254	560
Core Cowl	104	230
Centerbody (Nozzle Plug)	64	140
Mixer	138	305
Reverser Δ Weight	345†	760†
Mount	73	160
Total Installation	1,690	3,725
Engine	3,670	8,100
Total Pod	5,360	11,825

† Note‡: Total reverser weight per standard bookkeeping = 583 kg (1,285 lbs); but, since some parts such as cowling are required anyway, only 345 kg (760 lbs) extra was required to add commercial reverser.

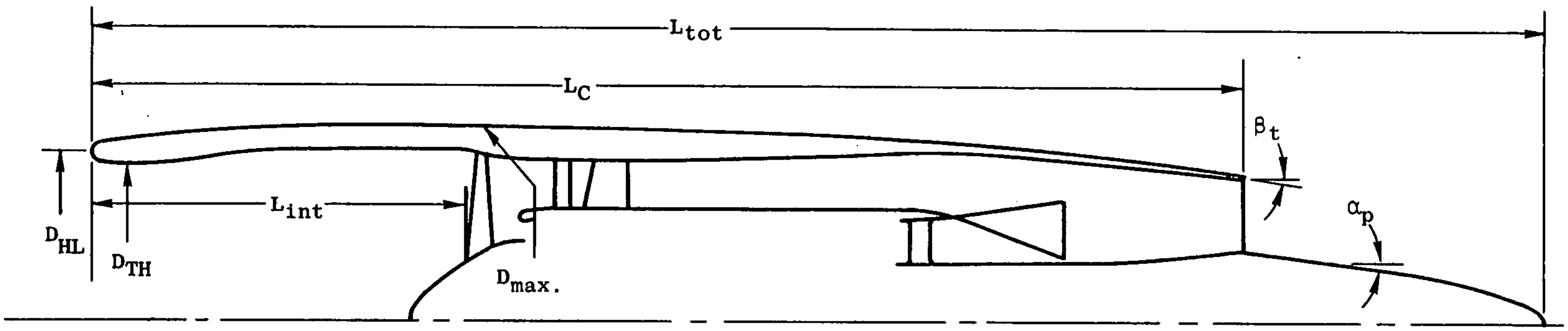
‡ Note does not include aircraft accessories or equipment.

TABLE XXVII. ATT No. 2 ADVANCED FEATURES, BASIC ENGINE.

1. Tip-Shrouded, Lightweight Fan Blades.
2. Fail-Safe Design Concepts on Fan and Core Turbine Discs.
3. Composite Blading on Booster and Front End of Core Compressor.
4. Casing Treatment on Booster and Core Compressor (Stall Margin).
5. Water Injection for Engine Design (as Well as Emissions).
6. Composite Fan Frame Struts.
7. Interstage Extraction and Bore Entry for Core Turbine Cooling.
8. Double-Annular Combustor.
9. Laser-Drilled Film or Film Impingement Turbine Blades.
10. Advanced Materials (Beyond ATT No. 1).
11. Control and Accessory Features (Beyond ATT No. 1).

TABLE XXVIII. ATT No. 2 BASIC ENGINE WEIGHT.

Item of Related Weight	% Reduction Versus ATT No. 1
Fan Related Weight	10 to 40%
Core Related Weight	25 to 45%
Fan Turbine Related Weight	0 to 10%
Other Related Weight	0 to 5%
Total Effect	12 to 32%



Engine	Cruise M_o	Inlet	$D_{max.}$ m/in.	$\frac{D_{HL}}{D_{max.}}$	$\frac{D_{HL}}{D_{TH}}$	$\frac{L_{int}}{D_{TH}}$	Equivalent Fineness Ratio	$\frac{L_C}{D_{max.}}$	$\frac{L_{tot}}{D_{max.}}$	β rad/ °	α rad/ °
ATT No. 1	0.98	BID	2.44/96	0.88	1.09	1.32	6.4	3.12	3.94	0.113/6.5	0.140/8
ATT No. 1	0.98	Flex.	2.44/96	0.88	1.09	1.24	6.4	3.06	3.87	0.113/6.5	0.140/8
ATT No. 1	0.90	Fixed	2.51/98.8	0.88	1.123	1.28	6.3	3.00	3.8	0.140/8	0.140/8
ATT No. 2	0.98	BID	2.36/93	0.88	1.07	1.26	6.2	3.16	3.7	0.122/7	0.140/8

Figure 39. ATT Engine Installation Dimensions.

along with a smaller contraction ratio such that clearance over the fan tip was comparable to that for engine No. 1. With these modifications, a 0.076 m (3 inch) nacelle diameter reduction, which may facilitate engine/aircraft integration, is possible.

Three accessory gearbox locations, as shown in Figure 40, were studied. The split accessory configuration was judged unacceptable from the accessibility aspect; the internally mounted accessories which were configured to maintain a circular nacelle did not provide a net performance gain since the internal losses balanced the small external drag gain; the conventional bottom-mounted accessories (nonsymmetrical nacelle) which provide maximum accessibility therefore were selected, pending additional aeromechanical studies and testing. Core-engine-mounted accessories also were studied but were rejected on the basis of higher fire hazards and poorer accessibility.

Exhaust Nozzle

Three exhaust nozzle configurations were evaluated (Figure 41) on a preliminary basis and a plug nozzle was selected since, for the cruise design pressure ratio of this application (3.3), it can provide the desirable thrust coefficient characteristics of a low-area-ratio, convergent-divergent nozzle with less weight penalty. For both the conical and C-D nozzles, the outer cowl would need to be considerably longer to maintain the same low nacelle boattail angles considered desirable for this high Mach application. However, the advantages identified in the course of the study for the plug nozzle are marginal, and the choice which was made on an isolated nacelle basis should be considered tentative at this time and reexamined in the context of each specific installation.

Nacelle Drag

Isolated nacelle drag for both engines at Mach 0.98 is of the order of 5% of net cruise thrust; it is about 1/2% higher than for the 0.90 Mach number case, based on conventional subsonic drag calculation methods. It is recognized that interference effects associated with the near sonic flight regime of this application ($M = 0.95 - 0.98$) will require experimental work to minimize these effects for each specific engine/airplane configuration. The pressure drag is determined based on an equivalent fineness ratio correlation as illustrated on Figure 42. Friction drag includes corrections for compressibility, supervelocity, and surface roughness effects. The effect of the accessory fairing on nacelle drag for externally bottom-mounted accessories is only of the order of 0.1 - 0.2% thrust, as indicated on Figure 42 which shows a drag comparison between a circular nacelle (no accessories) and one with the accessory fairing. Since the Mach 0.98 nacelle is slimmer, the drag penalty of the accessory bulge is larger than for the Mach 0.90 nacelle.

Reverse Thrust

The thrust reverser system for the ATT engines consists of a fan cascade reverser similar to the CF6-6 and CF6-50 engines and a core flow aerodynamic

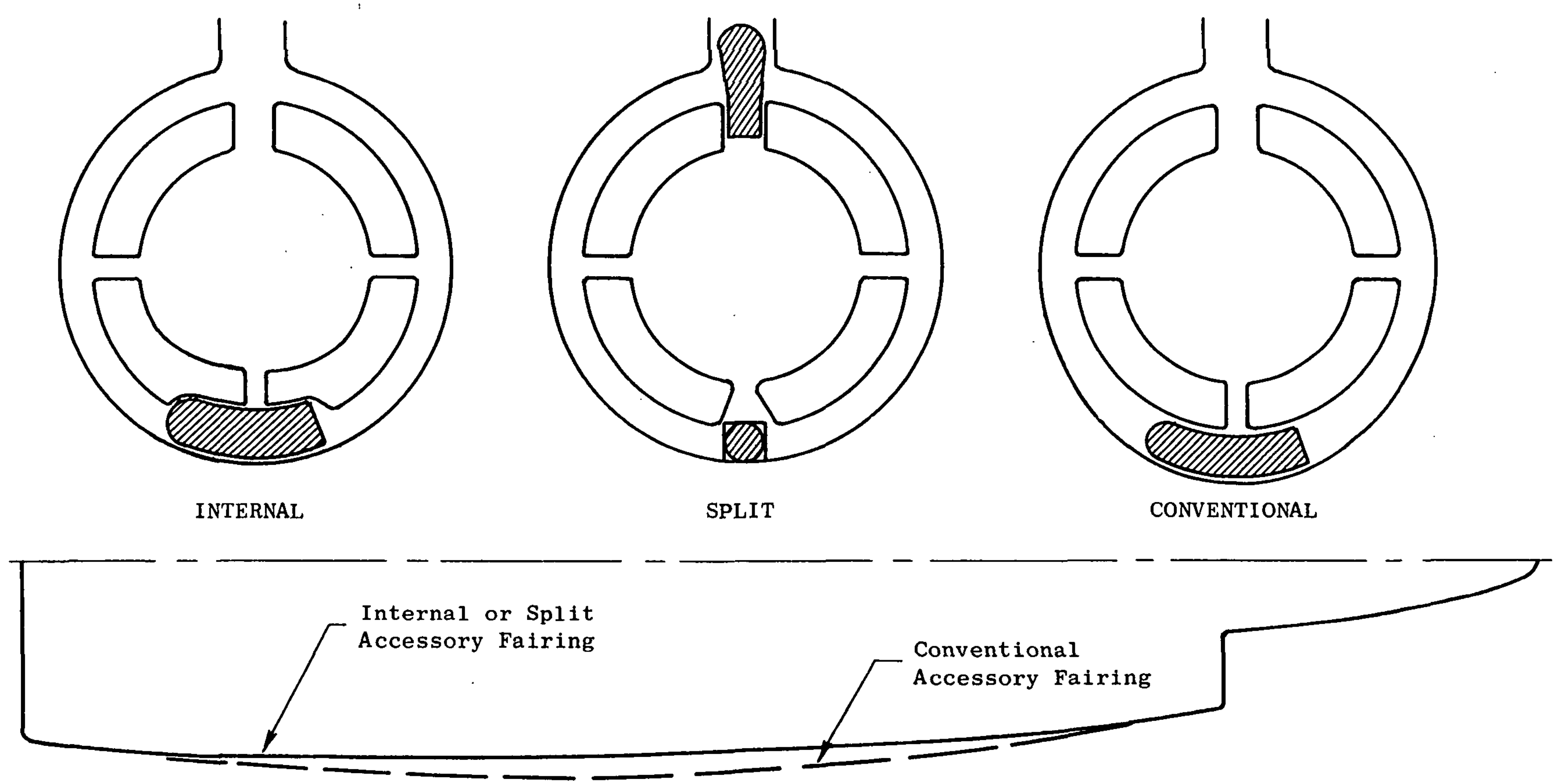


Figure 40. Accessory Gearbox Location.

Boattail Angle (β_t) = 0.11 to 0.12 radian (6.5°-7°) in All Cases.

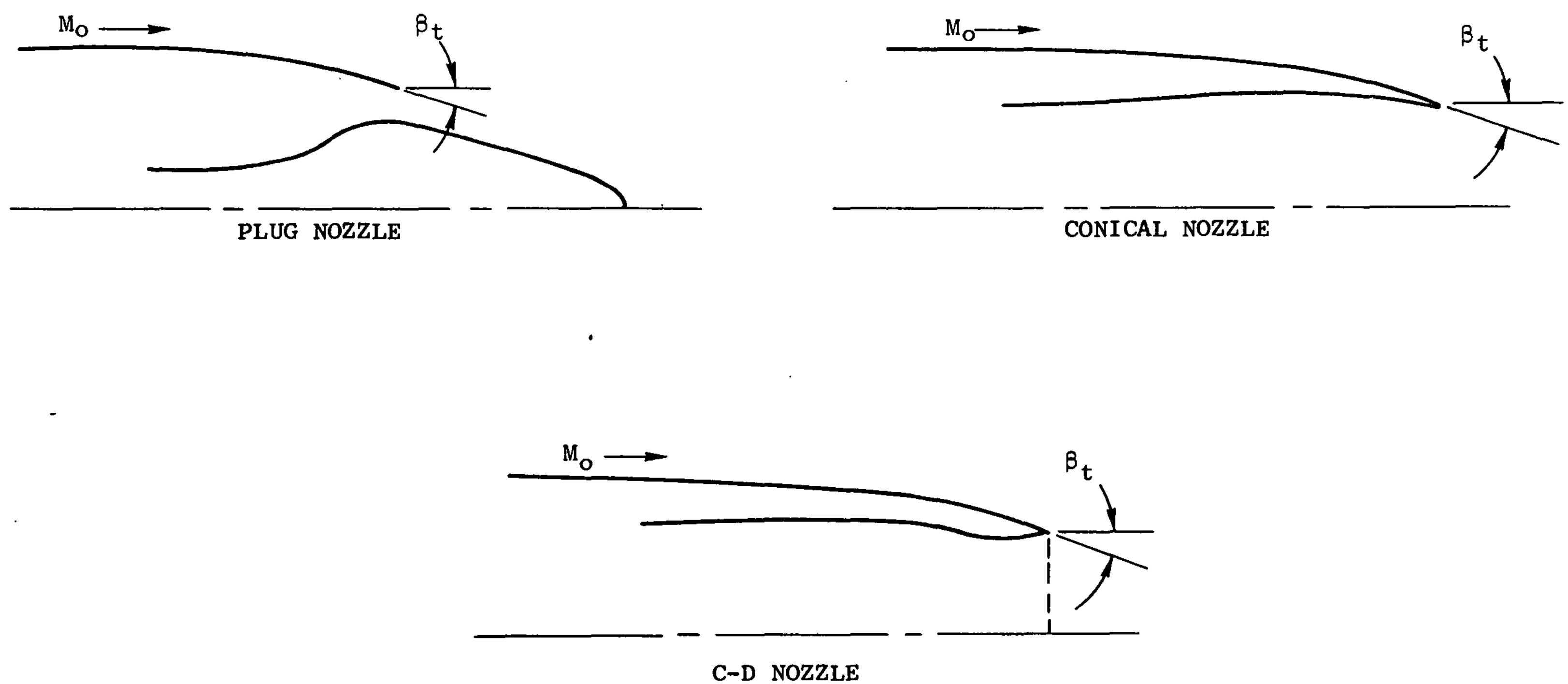


Figure 41. Exhaust Nozzle Candidates.

- Isolated Nacelle/No Interference

Engine	Cruise M_o	Nacelle Total Drag/FN	
		Circular Nacelle	W/Acc. Fairing
ATT No. 1	0.98	0.049	0.051
ATT No. 1	0.90	0.045	0.046

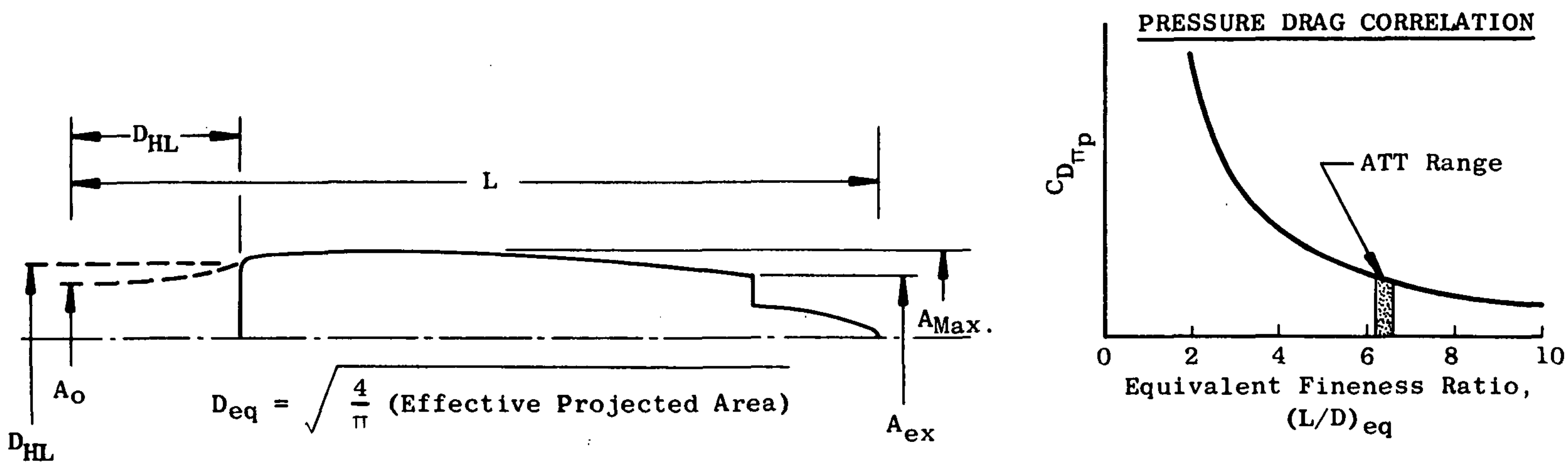


Figure 42. External Drag Comparison, M = 0.98 and M = 0.90.

thrust spoiler, as illustrated schematically in Figure 43. The aerodynamic thrust spoiler is a "built-in" feature of the mixed exhaust configuration which duplicates, without moving parts, the effects that could be obtained in a separate exhaust system with a variable exhaust nozzle capable of large exhaust area variations.

The fan flow cascade reverser performance is dependent on the flow tailoring requirements of specific installations in the reverse thrust mode of operation. Generally, it is desirable to skew some of the reverser cascade boxes to avoid impingement of the flow on the ground in order to minimize engine reingestion at low forward aircraft speeds and possible foreign object damage. Depending on the installation, it also may be desirable to avoid impingement of the flow on certain aircraft surfaces; although, with the low temperature fan exhaust flow, this generally is not a major problem.

For the ATT studies, an efflux angle (β_2) of 0.908 radian (52°) was chosen, based on previous experience with the TF39 and CF6 fan thrust reversers. With appropriate tailoring, this efflux angle should permit operation in the reverse mode down to very low aircraft forward speeds. With this efflux angle and a typical installation [where 40% of the cascade boxes would be skewed at an angle (α) of 0.611 radian (35°) and a representative fan flow leakage of 3%] a fan reverser effectiveness of 51% (Cfg_R) could be achieved. Scale model tests with a partial mixer and exhaust configuration of similar proportions have shown that a substantial portion of the core thrust during the reverse thrust mode of operation can be spoiled effectively. The combination of these two factors provides the overall reverse thrust indicated in Figure 44. The higher reverse thrust capability of engine No. 2 is due to its higher fan bypass ratio and the smaller forward thrust generated by the smaller core flow.

Estimates for an alternate configuration that would reverse the complete exhaust flow also is shown in Figure 44. The much longer exhaust length that would be needed [of the order of 1.6m (40 inches)] makes it quite unattractive for the additional reverse thrust it can provide and , therefore, is not recommended.

The installation features for engine No. 1 (Mach 0.95 - 0.98 design) are summarized in Table XXIX. The same items apply to engine No. 2 except that the noise treatment required to achieve the lower noise goal of 15 EPNdB below FAR 36 is increased to two inlet plus two exhaust splitters, in addition to peripheral treatment as indicated in the next section. A typical high-fineness-ratio nacelle incorporating the above features (noise suppression splitters not shown) is illustrated in Figure 45.

NOISE

The noise calculation procedure is similar to that of Task I with refinements based on updated information utilizing, in particular, the NASA Quiet Engine Program high speed fan test results. The procedure is outlined in the flow chart of Figure 46. The established noise objectives are: 10 EPNdB and 15 EPNdB below FAR part 36 for engines 1 and 2, respectively,

$F_{reverse} = F_{R_{fan}} - F_{g_{core}} \approx 33\% \; F_{forward}$ (ATT No. 1)

Fan - Fixed Cascade

Core - Aerodynamic Spoiler

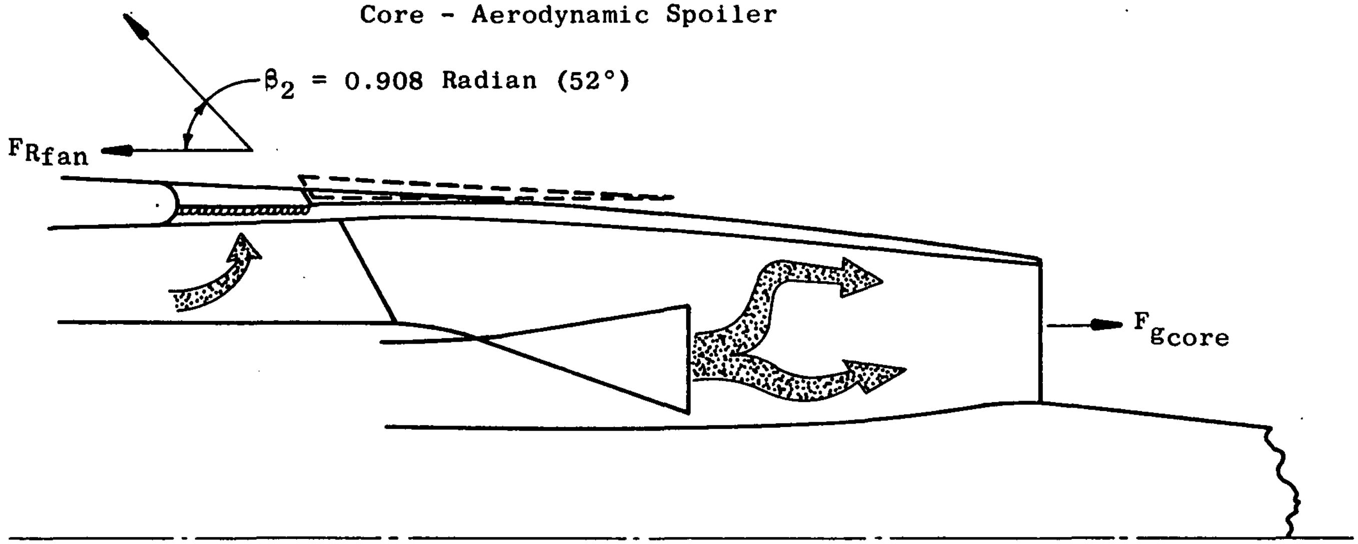
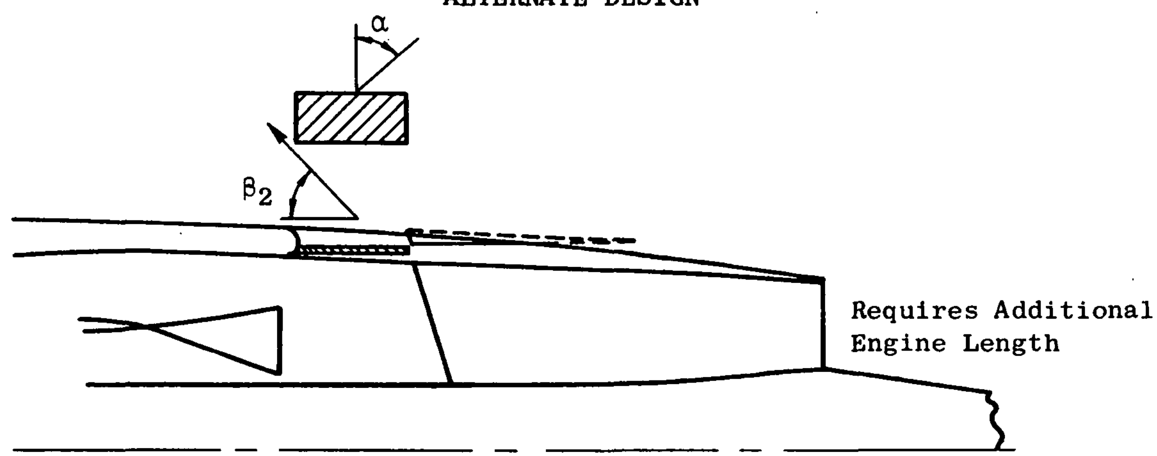


Figure 43. Thrust Reverser System, Mixed Exhaust.

NOMINAL DESIGN

T/R Type	Fan					Overall Reverse Thrust % of Forward Thrust
	Discharge β_2	Fan Leakage	Skewing		C_{FGR}	
			K	α		
Fan Cascade / Core Aero Spoiler	0.908 rad (52°)	3%	40%	0.611 rad (35°)	0.51	33 ATT No. 1 37 ATT No. 2

ALTERNATE DESIGN



NOT RECOMMENDED

Mixed Flow Cascade	0.908 rad (52°)	3%	40%	0.873 rad (50°)	0.48	45 ATT No. 1

Figure 44. Thrust Reverser Performance, Mixed Exhaust.

TABLE XXIX. ATT No. 1 INSTALLATION FEATURES.

(M = 0.95 to 0.98 Design)

1. High-Fineness-Ratio Nacelle.
2. Thin-Lip Inlet, Blow-In Doors or Variable-Lip Geometry.
3. Fan Stream Reverser, Cascade Type.
4. Mixed Exhaust, Aero Spoiler.
5. Externally Bottom-Mounted Accessories.
6. Low Angle Plug Nozzle.
7. Wall Suppression Plus Inlet Splitters for FAR-10.

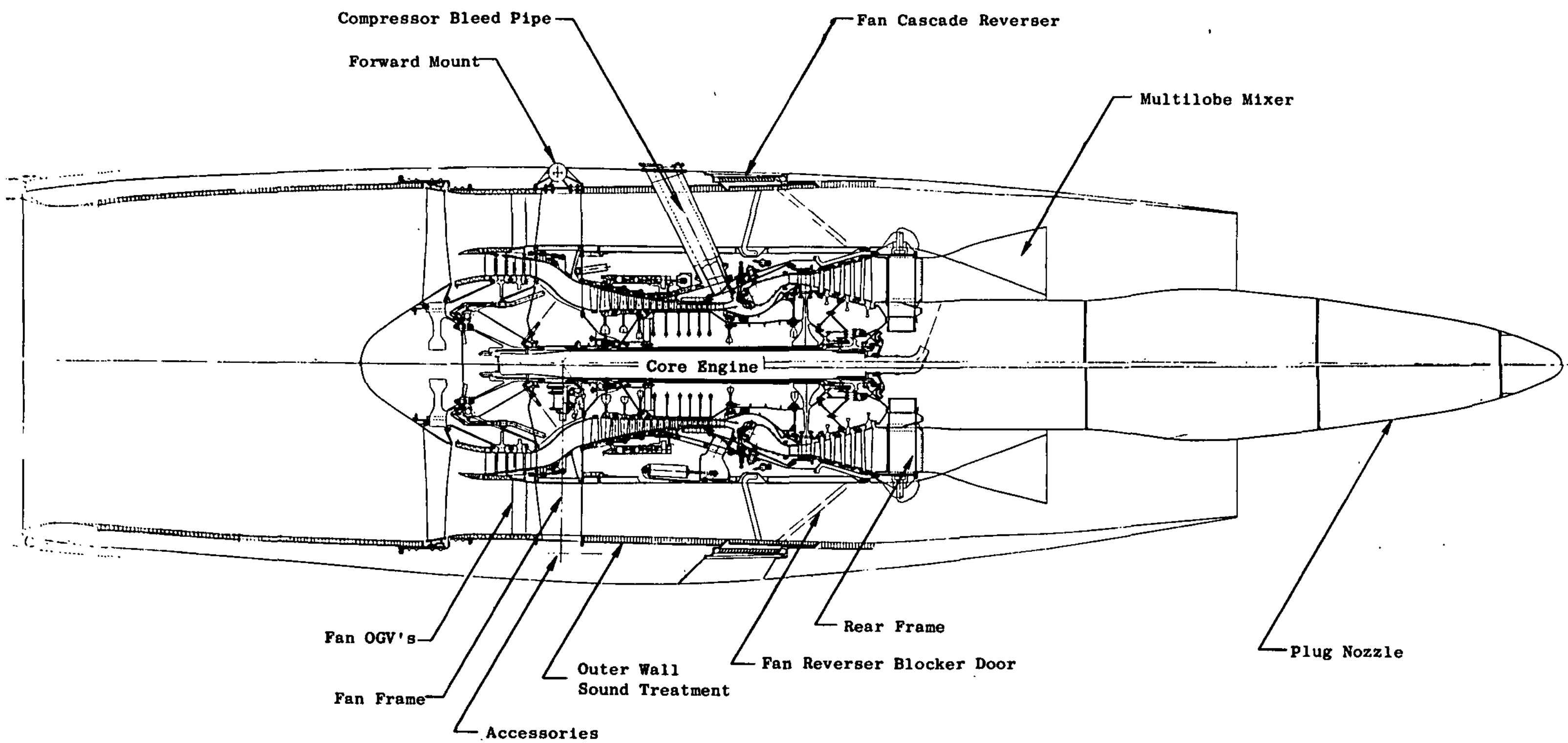


Figure 45. Typical Engine Installation, Mixed Exhaust, M = 0.98.

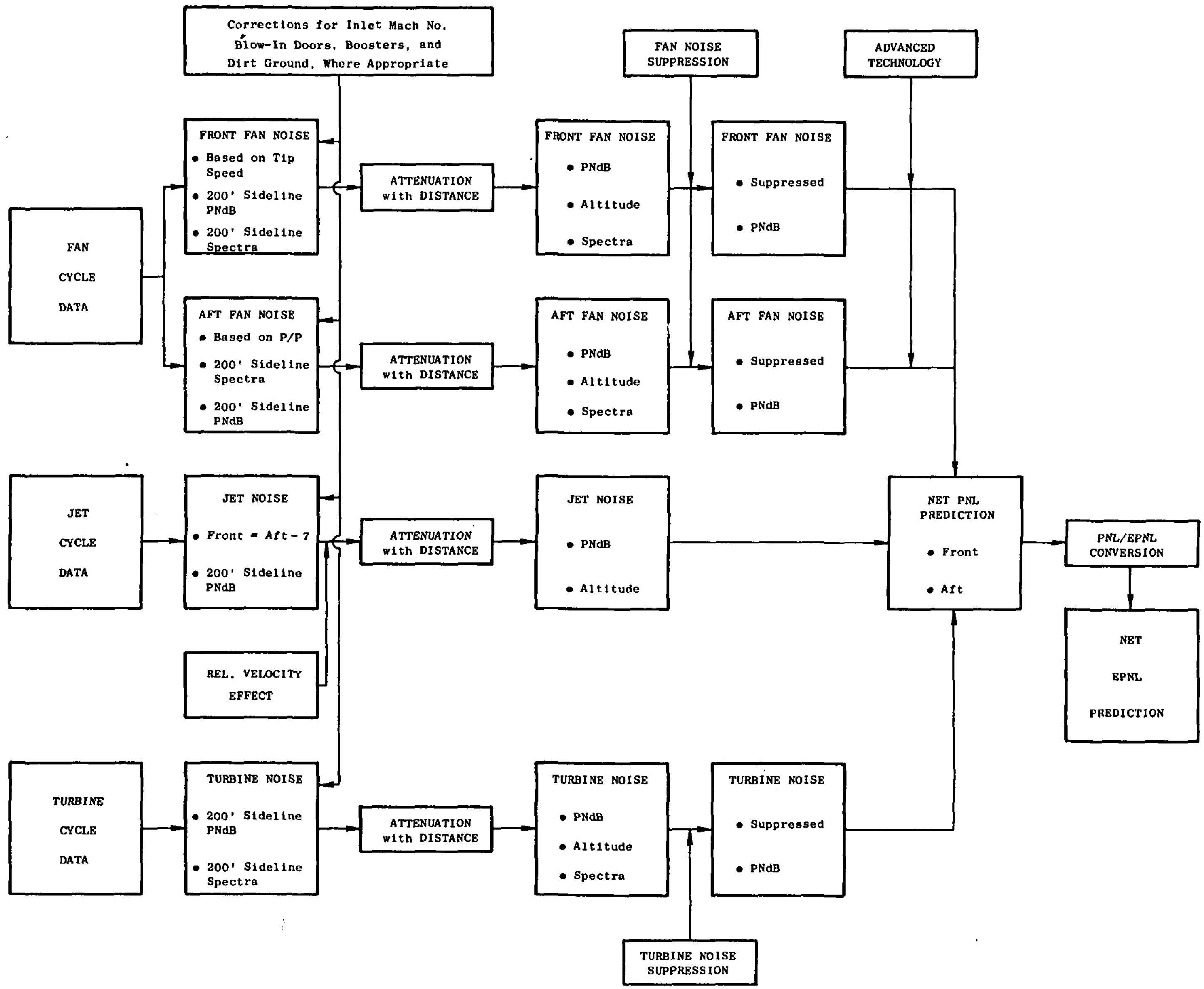


Figure 46. Task II, Noise Calculation Flowchart.

without operational procedures; and, a goal of 20 EPNdB below FAR 36 with novel flight procedures for engine No. 2. All the basic design features aimed at low source noise considered in Task I are incorporated in the designs of both engines. These include:

- Single-stage fan
- No inlet guide vanes (IGV's)
- Two true tip chords spacing between rotor and stator
- Blade/vane numbers set at a ratio of about 2
- Mixed-flow exhaust system

Airplane Flight Trajectory and Thrust Requirements

Based on the flight performance study of the 3-engine, Mach 0.98, 147,000 kg (325,000 lb) host airplane, the flight trajectory and thrust settings were established as shown in Figure 47. This figure applies to both engines. The normal procedure calls for takeoff at maximum thrust. Before the airplane reaches the 6482 m (3.5 nautical mile) overhead point, it cuts back to a thrust of 75%. At the 6482 m (3.5 nautical mile) overhead point, the airplane altitude is 488 meters (1600 feet) at a speed of Mach 0.26. For the normal 0.0524 radian (3°) glide slope approach, the required thrust at approach is estimated to be 30% of take-off thrust at the Mach 0.22 flight condition. The altitude at the 1852 m (1 nautical mile) point (from threshold) is 113 m (370 feet). During maximum-power takeoff, the airplane altitude is about 244 m (800 feet) when the maximum noise is heard at the 457m (1400 feet) sideline point.

Acoustic Treatment Design

Three levels of suppression were considered for each engine, as follows:

- Minimum - nacelle wall treatment only
- Moderate - wall treatment plus single inlet splitter
- Maximum - wall treatment plus 2 inlet and 2 short aft splitters

Consistent with the basic ground rule, no source noise reduction is assumed for Engine 1. However, calculations are carried out on Engine 2 with and without the use of a 5 PNdB source reduction associated with advanced technology.

Two-phase suppression is used in all cases. In the inlet, 60% of the available treatment length is designed for a higher frequency "tuning" and 40% for a lower frequency "tuning." In the case of exhaust duct wall treatment, the total length of the treatment is held constant, and the

• Airplane TOGW = 147,420 kg (325,000 lbs).

• 3 Engines

• Sea Level Static Thrust Per Engine = 156 kN (35,000 lbs).

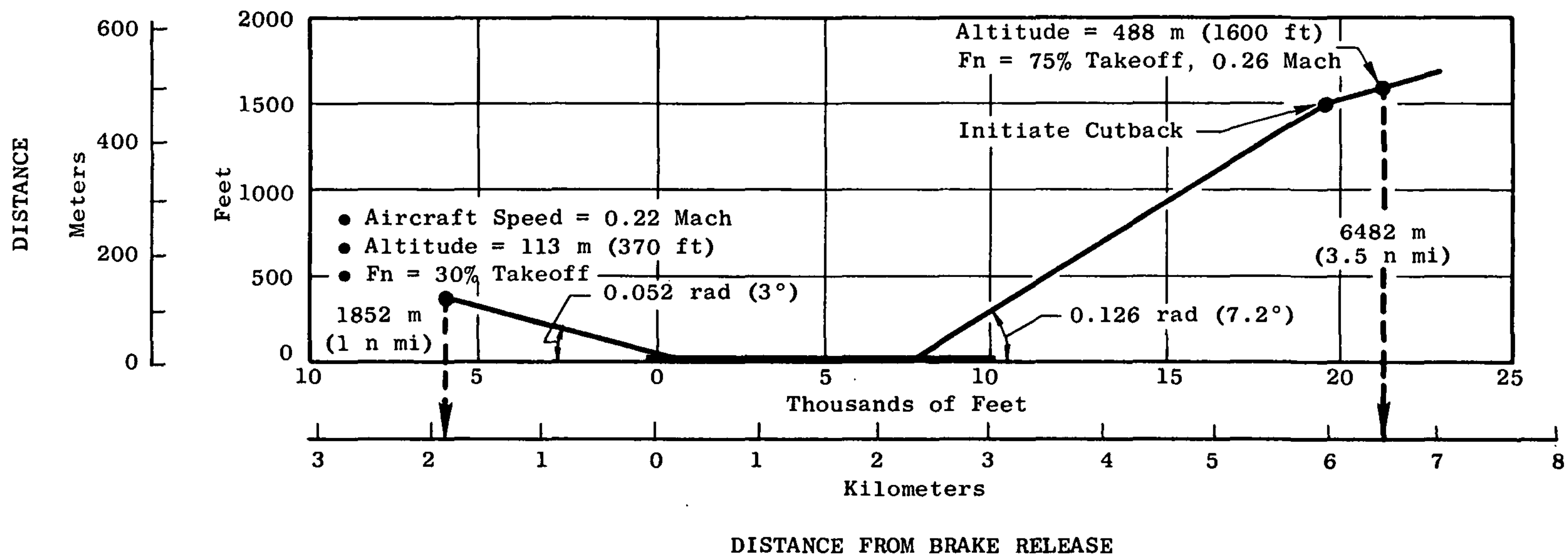


Figure 47. Standard Take-off and Approach Airplane Trajectories (M = 0.98 A/C).

relative lengths of the primary and secondary treatments are optimized. The lower frequency treatment was placed on the splitters and the surrounding wall region, while the remainder of the duct was designed to a lower frequency. The lower frequency treatment was divided into two sections, one immediately behind the fan and the other following the splitters, to minimize the treatment thickness in the splitter region.

Based on the suppression study, the following configurations were selected:

Engine No. 1, to meet FAR 36 - 10 EPNdB

- Full wall suppression plus 1 inlet splitter
- Treatment at turbine discharge (5 PNdB reduction)

General dimensions of the suppression configuration and estimated noise reduction are given in Figure 48.

Engine No. 2, to meet FAR 36 - 15 EPNdB with Advanced Technology

- Full nacelle wall treatment
- 2 inlet splitters and 2 short aft splitters
- More extensive turbine noise treatment (10 PNdB reduction required)

General dimensions of suppression configuration and estimated noise reduction are given in Figures 49 (A) and (B).

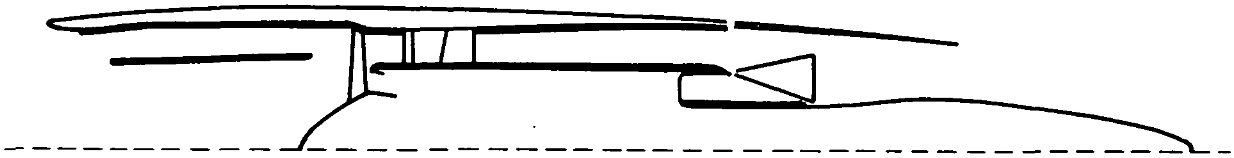
Noise Estimates

Standard Operational Procedures

Estimated EPNdB levels and ΔEPNdB traded levels (relative to established noise goals) for ATT Engines 1 and 2 and with different applied levels of nacelle suppression are summarized in Tables XXX and XXXI (A). Current technology fan source noise is assumed for Engine 1, while both current and advanced (i.e., 5 PNdB source reduction) technology fan source levels are considered for Engine 2. The selected suppression configurations described above are indicated in the tables by blocking.

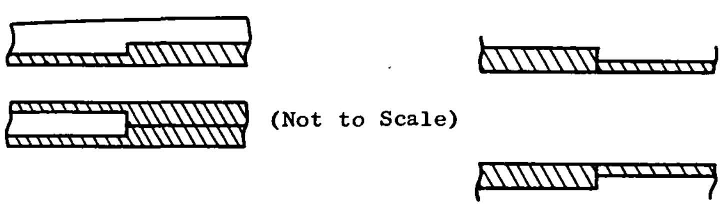
Two-Position A_8 and Novel Aircraft Operational Procedures

Engine No. 2 with the selected suppression configuration and with normal operational procedures, as shown in Table XXXI (B), cannot meet the FAR 36 - 20 EPNdB objective. There are two principal reasons for this: (1) jet noise is too high at the 457 m (1500 foot) sideline point during takeoff, and (2) fan noise level is too high at approach. Two approaches toward reducing the noise were investigated.



Parameter	Inlet Wall Treatment	Inlet Splitter	Exhaust Wall Treatment
$A_{treatment}$ (m^2/ft^2)	13/140	13.8/149	27.7/298
L (m/in.)	2.16/85	1.57/62	2.84/112
$L_{effective}$ (m/in.)	1.75/69†	1.27/50†	2.29/90
H (m/in.)	0.27/10.5	0.27/10.5	0.33/13
$M_{takeoff}$	0.6	0.6	0.46/0.6
$M_{approach}$	0.3	0.3	0.37/0.47
f_{design} (Hz)	3150/1600	3150/1600	1250/3150
$(L/H)_{average\ effectiveness}$	5.7	5.7	7.0
H/λ	2.4/1.2	2.4/1.2	1.2/3.0
t (cm) (in.)	1.0/1.65 0.4/0.65	2.0/3.3‡ 0.8/1.3‡	4.3/1.3 1.7/0.5
	Inlet		Exhaust
Δ $PNdB_{takeoff}$	11.5		10
Δ $PNdB_{approach}$	11.0		11

Inlet Exhaust

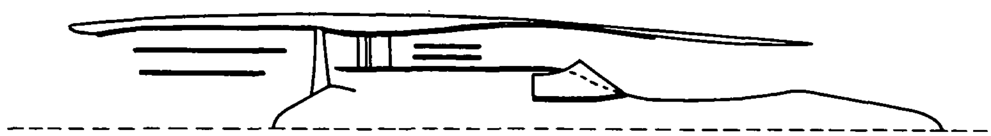


(Not to Scale)

A = Area
L = Length
H = Duct Height
f_{design} = Design Frequency
λ = Design Wavelength
t = Treatment Thickness

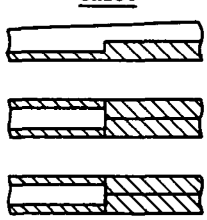
† 60% high frequency design, 40% low frequency design
‡ Total thicknes: [redacted]both sides of splitter)

Figure 48. ATT No. 1 Acoustic Treatment Design.



Parameter	Inlet			Exhaust		
	Wall Treatment	Outer Splitter	Inner Splitter	Wall Treatment	Outer Splitter	Inner Splitter
$A_{treatment}$ (m^2/ft^2)	12.5/135	14.5/156	8.5/92	24.4/263	7.0/75	5.9/64
L (m/in.)	2.16/85	1.57/62	1.31/51.5	2.74/108	0.69/27	0.69/27
$L_{effective}$ (m/in.)	1.75/69†	1.27/50†	1.07/42†	2.21/87	0.56/22	0.56/22
H (m) (in.)	0.21 8.4	0.21 8.4	0.21 8.4	0.12/0.43 4.7/17	0.12 4.7	0.12 4.7
$M_{takeoff}$	0.6	0.6	0.6	0.6/0.48	0.6	0.6
$M_{approach}$	0.3	0.3	0.3	0.47/0.37	0.47	0.47
f_{design} (Hz)	3150/1600	3150/1600	3150/1600	4000/1250	4000	4000
$(L/H)_{average\ effectiveness}$	7.1	6.0	5.5	13.5	4.7	4.7
H/λ	1.9/1.0	1.9/1.0	1.9/1.0	1.4/1.5	1.4	1.4
t (cm) (in.)	0.6/1.5 0.25/0.6	1.3/0.3‡ 0.5/1.2‡	1.3/0.3‡ 0.5/1.2‡	1.9/3.0 0.75/1.2	3.8‡ 1.5‡	3.8‡ 1.5‡
	Inlet			Exhaust		
Δ $PNdB_{takeoff}$	14			14		
Δ $PNdB_{approach}$	13			15		

Inlet



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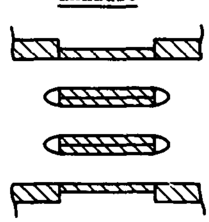
Exhaust



A = Area
L = Length
H = Duct Height
f_{design} = Design Frequency
λ = Design Wavelength
t = Treatment Thickness

† 60% high frequency design, 40% low frequency design
‡ Total thickness (both sides of splitter)

Figure 49. ATT No. 2 Acoustic Treatment Design.

TABLE XXX. ATT No. 1, ESTIMATED NOISE LEVELS.

- 3 Engines
- Standard +10° C (+18° F) Day
- Dirt/Grass Ground
- Fn = 156 kN (35,000 lbs) at Sea Level Static
- No Advanced Technology

FAR-10	96	93.5	96	TOGW = 147,420 kg (325,000 lbs)

Configuration	Sideline 457 m (1500 ft) 100% Fn	Takeoff 488 m (1600 ft) Altitude 75% Fn	Approach, 113 m (370 ft) Altitude 30% Fn	Traded Noise Reference, FAR-10
Bare Engine	104.3	103.6	107.0	+9.8
Inlet + Aft Wall Treatment	96.1	94.9	98.5	+1.4
1 Inlet Splitter + Wall Treatment §	95.5	93.4	96.2	-0.1
2 Inlet Splitters + 1 Aft Splitter + Wall Treatment	93.5	90.3	93.7	-2.7
1 Inlet Splitter + 1 Aft Splitter + Wall Treatment	93.9	92.0	95.2	-1.5

§ This suppression configuration is selected to meet Engine ATT No. 1 noise goal, FAR-36 minus 10 EPNdB.

TABLE XXXI. ATT No. 2, ESTIMATED NOISE LEVELS.

- 3 Engines
- Standard +10° C (+18° F) Day
- Dirt/Grass Ground
- Fn = 156 kN (35,000 lbs) at Sea Level Static

FAR-15	91	88.5	91	TOGW = 147,420 kg (325,000 lbs)
I. No Advanced Technology Configuration	Sideline 457 m (1500 ft) 100% Fn	Takeoff 488 m (1600 ft) Altitude 75% Fn	Approach 113 m (370 ft) Altitude 30% Fn	Traded Noise Reference, FAR-15
Bare Engine	104.3	103.5	108.2	+15.2
Inlet + Aft Wall Treatment	96.7	94.9	100.0	+7.1
1 Inlet Splitter + Wall Treatment	95.9	94.0	97.2	+5.6
2 Inlet + 2 Aft Splitters + Wall Treatment	93.2	90.4	95.0	+2.7
II. Advanced Technology † Configuration	Sideline 457 m (1500 ft) 100% Fn	Takeoff 488 m (1600 ft) Altitude 75% Fn	Approach 113 m (370 ft) Altitude 30% Fn	Traded Noise Reference FAR-15
Bare Engine	100.1	98.6	103.5	+10.6
Inlet and Aft Wall Treatment	93.9	91.0	95.5	+3.3
1 Inlet Splitter + Wall Treatment	93.3	90.2	93.5	+1.9
2 Inlet + 2 Aft Splitters + Wall Treatment ‡	91.5	87.4	90.6	-0.3
FAR-20	86	83.5	86	TOGW = 147,420 kg (325,000 lbs)
III. Operational Procedures	Sideline 457 m (1500 ft) 100% Fn	Takeoff 518 m (1700 ft) Altitude 50% Fn	Approach 152 m (500 ft) Altitude 30% Fn	Traded Noise Reference FAR-20
2 Inlet + 2 Aft Splitters + Wall Treatment, Also with 15% Open A_8, and Advanced Technology †	89.6	82.6	78.3	+1.6

† 5 PNdB Fan Source Noise Reduction.
‡ This Suppression Configuration Is Selected to Meet Engine ATT No. 2 (with Advanced Technology) Noise Goal of FAR-36 Minus 15 EPNdB.

First, by incorporating a two-position jet nozzle area (A_8) design, jet noise at takeoff can be reduced by high flowing the engine (i.e., maintaining constant thrust by an increase in fan speed and an increase in weight flow, but with reduced exhaust velocity). Figure 50 shows that with an A_8 increase of 15%, which is deemed appropriate, a jet noise reduction of about 2.5 PNdB can be achieved at takeoff.

Second, operational procedures of the airplane were modified to incorporate a 0.1048 radian (6°) and 0.524 radian (3°) two-segment approach (Figure 51, Case C) and a special take-off trajectory whereby the airplane retracts flaps and accelerates early, thus allowing the airplane to achieve a substantially higher speed over the community noise measurement point which, in turn, permits a greater amount of power cutback (Figure 52, Case C).

By adopting this approach, the cut-back thrust over the 6482 m (3.5 nautical mile) point is 50% at an altitude of about 518 m (1700 feet). The approach thrust over the landing reference point is only 16%, with the airplane at an altitude of 152 m (500 feet). Operation of the engines at these reduced powers (relative to normal operations) brings about significant fan and jet noise reduction.

The final estimated EPNdB noise levels for Engine No. 2, incorporating the two-position nozzle and special operational procedures just described, are presented in Table XXXI(B). A level of FAR 36 minus 18 on a traded basis is achieved, which is short of meeting the -20 EPNdB objective.

Noise Contour Study

In assessing an aircraft's impact on airport neighborhood noise levels, it is important to examine the EPNL contours or "footprints" created during approach and takeoff. A study therefore was performed to estimate the noise footprints of the ATT engines under a variety of take-off and approach conditions. Selected for study are the FAR 36 minus 10 configurations of engine No. 1 (one inlet splitter with aft duct wall treatment) and the FAR 36 minus 15 configuration of engine No. 2 (two inlet plus two short aft splitters with wall treatment). The various approach and take-off paths considered are shown in Figures 51 and 52, respectively. The cases considered for engine No. 1 are a standard [0.0524 radian (3°)] approach with a straight climb-out takeoff and then a standard approach with a cutback after takeoff. For engine No. 2, four cases are considered: first, a repeat of the engine No. 1 cases; then a 0.1048 radian (6°) approach down to 76 m (250 feet) altitude coupled with a takeoff including an acceleration between 122 and 152 meters (400 and 500 feet) altitude and followed by a severe cutback. For these calculations, the cutback after takeoff was made exactly at the 6482 m (3.5 nautical mile) point, resulting in a slightly higher altitude at this measuring point than that altitude used for the basic noise calculations where cutbacks were initiated earlier. This discrepancy, however, has only a small effect on the contour shapes and areas.

The conservative assumption is made that the effective perceived noise levels are attenuated according to the inverse square law with distance.

- ATT Engine No. 2
- Standard +17.2° C (+31° F) Day
- Sea Level
- M = 0.25

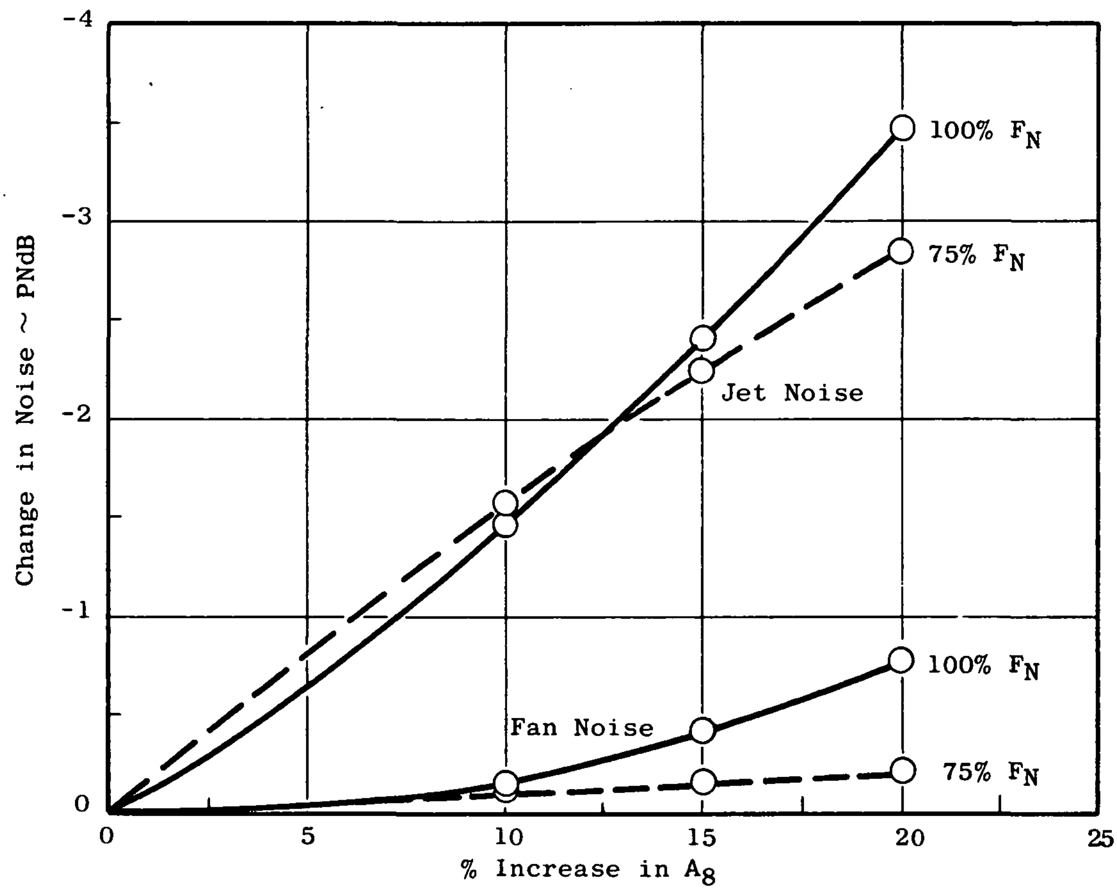


Figure 50. Effect of Exhaust Nozzle Area Increase on Noise Levels.

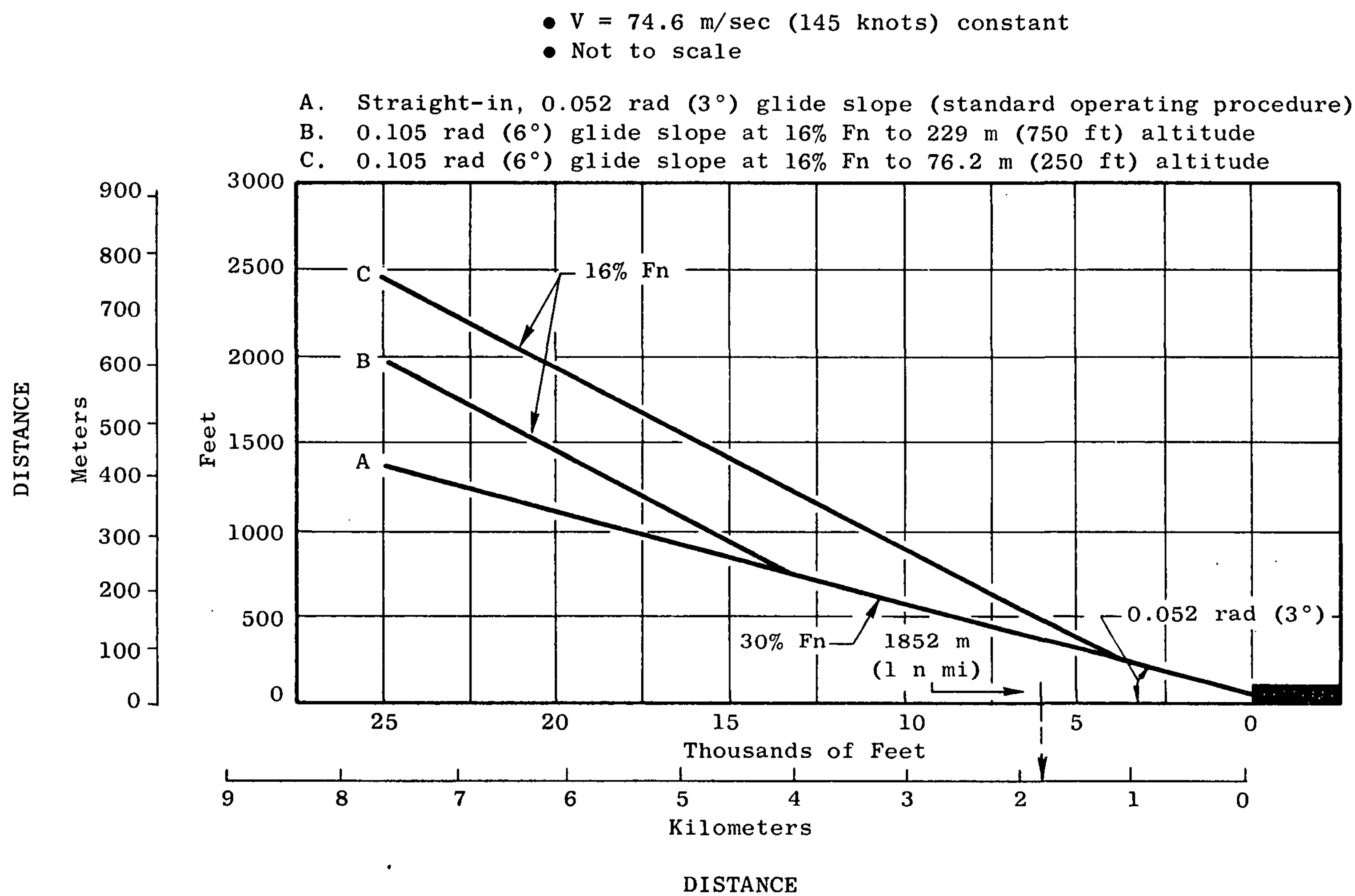


Figure 51. Aircraft Trajectories with Operational Procedures, Approach.

A. Straight-out takeoff, 100% Fn, no cutback, V = 92.6 m/sec (180 knots)

B. Straight-out to 6482 m (3.5 n mi), 100% Fn, cut back to 75% Fn at 6482 m (3.5 n mi) (standard operating procedure)

C. Trajectory as indicated in diagram, cut back to 50% Fn at 6482 m (3.5 n mi)

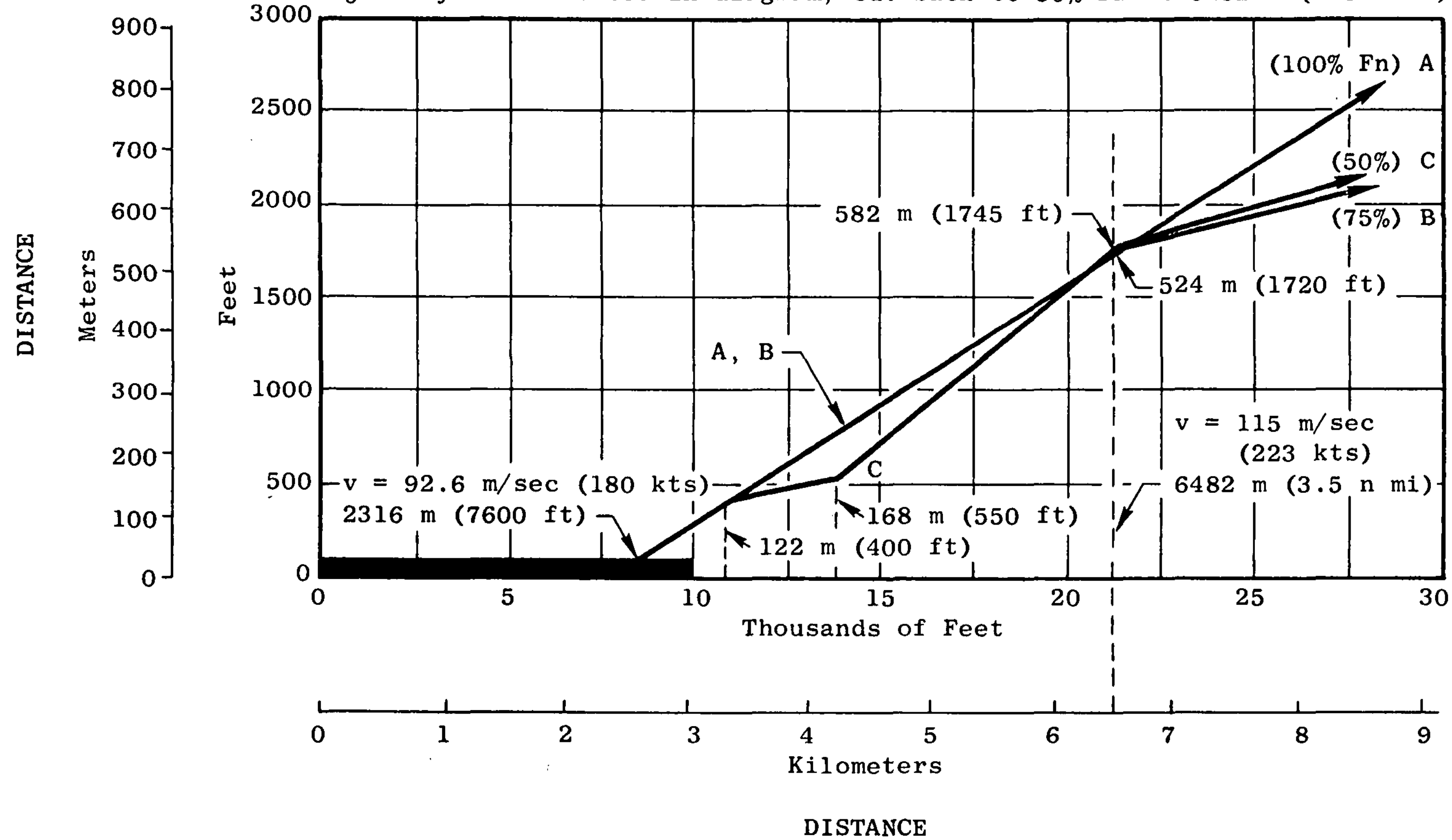


Figure 52. Aircraft Trajectories with Operational Procedures, Takeoff.

The resultant noise contours are shown in Figures 53 and 54. Note that while engine No. 1 requires a cutback at 6482 m (3.5 nautical miles) after brake release to meet FAR 36 minus 10, an examination of the results shows that power cutback has a negligible effect on the 80 EPNdB area, but reduces the 90 EPNdB exposure area by approximately 20%.

The results for engine No. 2 indicate a significant reduction with power cutback for the 80 EPNdB contour, but little power cutback effect for the 90 EPNdB countours. Comparing engines 1 and 2 (both with standard operating procedure-i.e., cutback at the community noise point), engine 2 (being basically 5 EPNdB quieter by design) has noise exposure areas of approximately 50% of those for engine No. 1.

Special operating procedures, like the use of the two-segment approach and more drastic power cutback made possible by retracting flaps early, have very significant impacts in reducing the noise exposure area, particularly in the lower level, further-out part of the airport neighborhood. A 60% reduction is realized in the 80 EPNdB contour between the "worst" and "best" operating procedures.

Noise Comparisons

A noise comparison between ATT engine No. 1 and the CF6-6D engine which powers the DC-10-10 aircraft is shown below:

61 m (200 feet) Sideline Single Engine, Max. PNdB, Hard Surface

	ATT No. 1 Scaled to CF6-6 Size	CF6-6 178 kN (40,000 lbs) Take-off Thrust	Scaled ATT No. 1 Minus CF6-6 (ΔPNdB)
Unsuppressed			
Takeoff	127.7	126	+1.7
30% Fn, 0.2 Mach	114.4	114	+0.4
Wall Suppression			
Takeoff	120.2	122	-1.8
30% Fn, 0.2 Mach	106.7	109	-2.3

The basic unsuppressed scaled ATT engine No. 1 is seen to be actually slightly higher in noise level. This is due primarily to the fact that the ATT engine cycle, to be compatible with the ATT mission requirements, calls for a higher specific thrust. Also, a noise penalty is assigned to the ATT engine associated with the use of inlet blow-in-doors. Thus, at takeoff, fan pressure ratio for the ATT engine No. 1 is 1.75 as compared to 1.56 for the CF6-6. The higher noise

- FAR-36 -10 Configuration, -1 Inlet Splitter with Wall Treatment
- See Figures 51 and 52 for Detailed Flight Trajectory

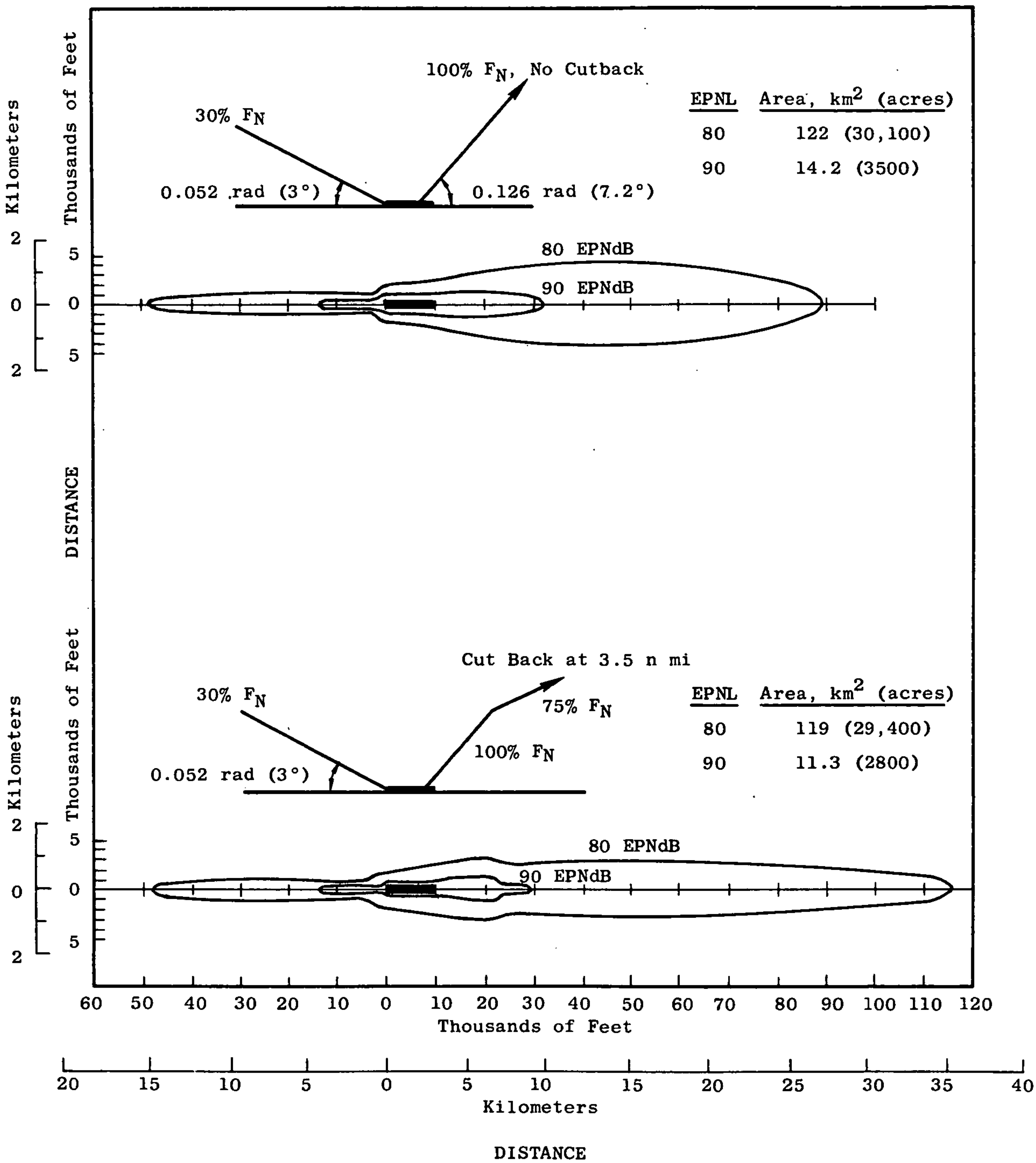
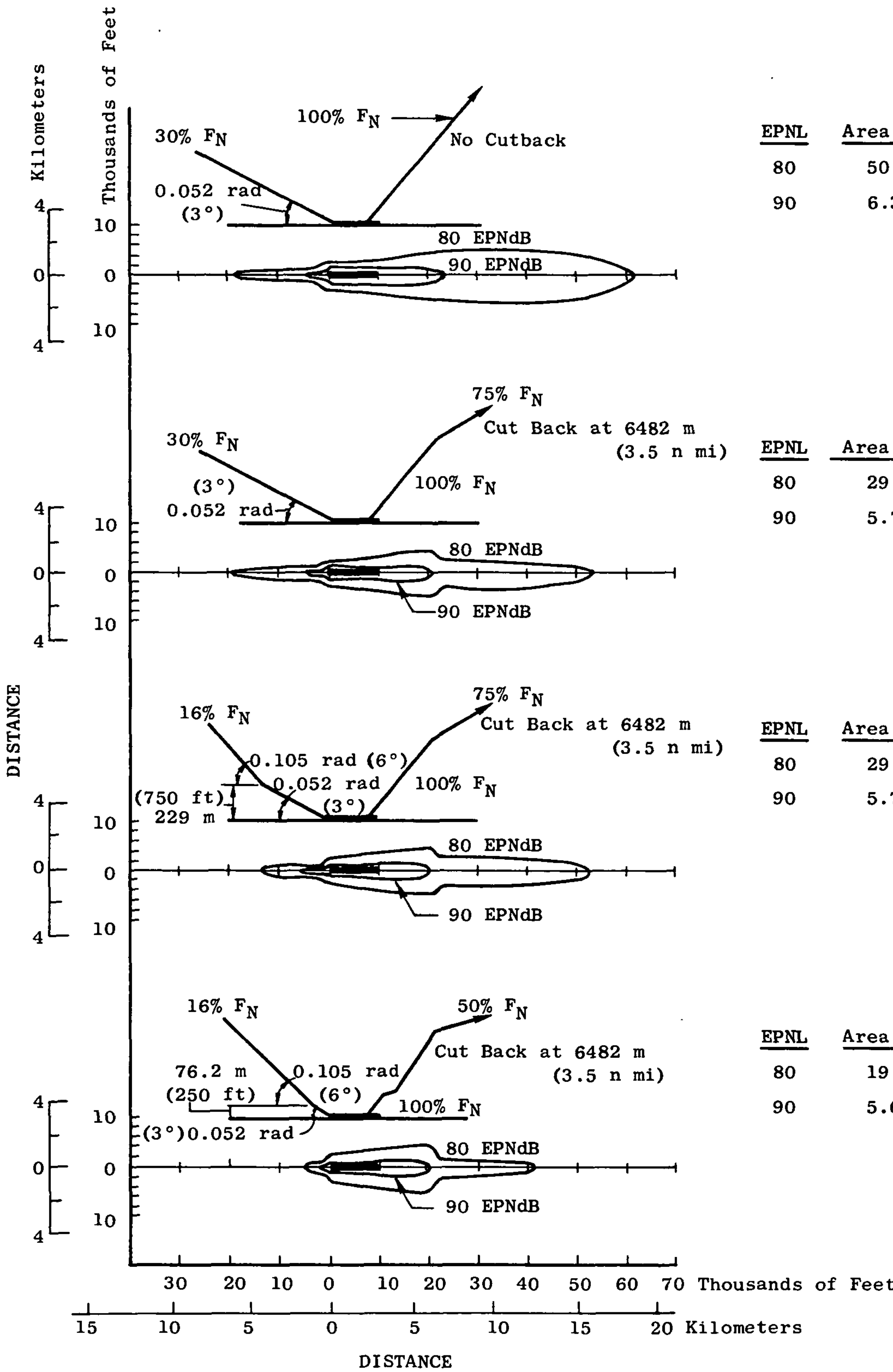


Figure 53. ATT No. 1 Noise Contours.



EPNL	Area, km^2 (acres)
80	50.2 (12,400)
90	6.3 (1550)

EPNL	Area, km^2 (acres)
80	29.5 (7300)
90	5.7 (1410)

EPNL	Area, km^2 (acres)
80	29.1 (7180)
90	5.7 (1420)

EPNL	Area, km^2 (acres)
80	19.3 (4780)
90	5.6 (1390)

Figure 54. ATT No. 2 Noise Contours.

level due to fan pressure ratio effect is partly offset by the somewhat larger blade/vane spacing on the ATT engine No. 1 (2 against about 1.25).

With peripheral treatment, ATT engine No. 1, by virtue of its longer nacelle, enjoys considerably more nacelle suppression. Hence, the 61 m (200 feet) sideline suppressed noise level for the scaled ATT No. 1 is about 2 to 2.5 PNdB lower than the CF6-6 engine.

A comparison of Tri-Jet EPNdB noise levels in flight powered by scaled ATT No. 1 and CF6-6 engines is shown below:

Flight EPNdB, Wall Suppression Only; 3 Engines, Dirt Ground

Total Take-off Thrust = 534 kN (120,000 lbs)

Parameter	Scaled ATT No. 1	CF6-6/DC-10-10	Scaled ATT minus CF6-6
Sideline, 457 m (1500 feet)	96.6	96	+0.6
Community	95.5 (cutback)	98 (no cutback)	-2.5
	488 m (1600 ft.)	457 m (1500 ft.)	
Approach	99 (30% Fn)	102 (35% Fn)	-3.0
		105 (45% Fn)	-6.0

The ATT Tri-Jet powered by three scaled ATT No. 1 engines would have lower noise levels than the DC-10-10 at the community and approach points, but would be only comparable to the DC-10-10 at the take-off sideline point. In the latter case, the effects of higher inlet noise (due to higher tip speed) on duration and the higher jet noise level (due to higher specific thrust) of the ATT engine are the cause. On a traded noise basis, the scaled ATT engine 1 noise level, with wall suppression, is still lower by about 2.5 EPNdB.

It is noted, of course, that ATT engine No. 2 with advanced technology and wall suppression only attains a level of about 11.7 EPNdB below FAR 36, while the DC-10-10 currently is achieving a level between 3 and 6 EPNdB below FAR 36, depending on the flap setting at approach.

As a matter of interest and to provide additional perspective, Table XXXII compares the 90 EPNdB noise exposure areas for the ATT (engines 1 and 2), a 707/DC-8 turbofan-powered transport, and the DC-10-10 (GE CF6-6D) widebody transport. These noise contour analyses indicate that ATT engine No. 1 (with the standard one inlet splitter suppression configuration) has a 90 EPNdB contour area that is about half that of the DC-10-10 Tri-Jet. Advanced technology ATT engine No. 2, with its standard suppression configuration (2 inlet + 2 exhaust splitters), has a 90 EPNdB contour area that is approximately

TABLE XXXII. COMPARISON OF ATT NOISE CONTOUR AREAS WITH THOSE OF CURRENT AIRCRAFT.

Contour	ATT No. 1 (Standard Operating Procedure)†		ATT No. 2 (Standard Operating Procedure)‡		DC-10-10§		707/DC-8	
EPNdB	km^2	Acres	km^2	Acres	km^2	Acres	km^2	Acres
80	119	29,400	29.5	7,300	---	---	---	---
90	11.3	2,800	5.7	1,410	21.9	5,400	190.2	47,000
100	2.0	490	1.2	288	3.7	910	---	---

† Standard Suppression Configuration, Nacelle Wall Suppression + 1 Inlet Splitter.

‡ Standard Suppression Configuration, Nacelle Wall Suppression + 2 Inlet and 2 Short Aft Splitters.

§ 0.873 rad (50°) Flap Setting at Approach.

NOTE: Area within Typical Major Airport Boundary: 12.1 to 20.2 km^2 (3,000 to 5,000 acres).

1/4 that of the DC-10-10. The ATT engine No. 2 90 EPNdB contour is approximately 1/30 that of the first generation turbofan 707/DC-8 airplanes.

Uncertainties in the Noise Estimates

ATT engines employ cycles and design features that are beyond the scope of actual noise test experience. For these reasons, there are considerable uncertainties (± 3 PNdB) regarding the fan and jet noise estimates and suppression design. Advanced technology programs are required to confirm study results and designs. A major aero-acoustics R&D effort is needed to accomplish the 5 PNdB fan source noise reduction assumed for engine No. 2.

EMISSIONS ESTIMATES

A summary of the predicted exhaust emissions levels with and without special controls is presented in Table XXXIII for both engines. Although the advanced carbureting combustors proposed for ATT application are projected to generate significantly lower quantities of pollutants at both idle and take-off conditions, they cannot meet the objective levels specified in this study. Without water injection into the combustor, the generation of oxides of nitrogen (NO_x) is approximately 4 to 7 times higher than the objective for engines 1 and 2, respectively. However, the goal can be met with relatively small quantities of water, as indicated. Likewise, idle emissions objectives cannot be met without some form of control to maintain high idle combustor efficiency. With these controls, however, the idle emissions objectives can be met, or possibly even exceeded, with the more advanced combustor and higher pressure ratio cycle of engine No. 2. Smoke levels can be met with either combustor without special controls.

EVALUATION OF RESULTS

Basis

The mission sensitivity factors used to compare the two advanced technology engines (Table XXXIV) are based on the Mach 0.98 host airplane described in Task I and revised economic ground rules specified by NASA which only affected the return on investment sensitivity factors due to the difference in revenue yield.

Comparison of ATT No. 1 and ATT No. 2

The payoff of advanced technologies and concepts embodied in engine No. 2, relative to engine No. 1, are presented in Table XXXV in terms of variations in aircraft take-off gross weight (TOGW), direct operating cost (DOC), and return on investment (ROI). Both engines have equivalent wall sound suppression treatment and, for the same specific thrust, have nearly the same noise on a traded basis.

The reduction of engine weight for engine No. 2, relative to engine No. 1, is shown as a range in Column 2 of Table XXXV. As discussed earlier, the weight of engine No. 2 depends on the degree to which the design implementation of the various advanced concepts described is successful. Cost uncertainties were

TABLE XXXIII. PREDICTED EMISSIONS LEVELS, ATT No. 1 AND No. 2.

Parameter	Engine Designations	
	ATT No. 1	ATT No. 2
Pressure Ratio at Sea Level Takeoff	27	33
NO at Takeoff without Water (3*)	11 to 15	18 to 22 g/kg Fuel
H_2O Required to Meet Objectives	2.0 to 2.5	2.5 to 3.0%
Combustion Efficiency at Idle	0.966	0.969
Nominal CO at Idle (40.0*)	60	55 g/kg Fuel
Nominal H/C at Idle (8.0*)	20	18 g/kg Fuel
Idle Emissions Control Technique	15% Compressor Exit Bleed	Single-Annulus Operation
Nominal CO with Control	40	30 g/kg Fuel
Nominal H/C with Control	7	Less than 4 g/kg Fuel
Maximum Smoke Level (15*) (SAE 1179)	15	15 SAE Number
(*) Study Objective Levels.		

TABLE XXXIV. MISSION SENSITIVITY FACTORS FOR M = 0.98 AIRCRAFT, TASK II.

- Constant Range and Payload
- Variable Gross Weight
- Engines Sized for Constant Cruise Thrust

Change	Effect Upon		
	TOGW	DOC	ROI§
+ 1% Installed sfc	+ 0.76%	+ 0.72%	- 0.46%
+ 218 kg Weight per Engine (+ 500 lbs)	+ 1.10%	+ 0.65%	- 0.45%
+ $10,000 Basic Engine Price	---	+ 0.14%	- 0.12%
+ $10,000 Reverser Price	---	+ 0.09%	- 0.09%
+ $10,000 Other Installation Price	---	+ 0.07%	- 0.09%

§ A 1% change in ROI represents an absolute change, as from 25% to 26%.

TABLE XXXV. MERIT FACTOR EVALUATION, ATT No. 1 VERSUS ATT No. 2.

- Mach 0.98 Aircraft
- 3 Engines
- Constant Installed Cruise Thrust
- Wall Treatment Only

		ATT No. 1	ATT No. 2
Noise Relative to FAR on Traded Basis		- 8.6 EPNdB	- 7.9 EPNdB

Parameter	Δ Parameter ATT No. 2 Minus ATT No. 1	ATT No. 2 Minus ATT No. 1		
		Δ TOGW	Δ DOC	Δ ROI
Installed sfc†	- 2.5%	- 1.9%	- 1.8%	+ 1.2%
Engine Weight	- 454 to 1180 kg (- 1000 to 2600 lbs)	- (2.2 to 5.7%)	- (1.3 to 3.4%)	+ (0.9 to 2.3%)
Total	---	- 4.1% to - 7.6%	- 3.1% to - 5.2%	+ 2.1% to + 3.5%

† 0.907 kg/sec (2 lbs/sec) interstage bleed, 74.6 kW (100 hp), η_r as scheduled.

judged too large at this time to include engine price effects.

The results indicate that, even when the most pessimistic engine weight reduction estimates are used, the payoff of advanced technologies and concepts considered for engine No. 2 is significant, with performance effects contributing roughly 50% of the potential improvement over engine No. 1.

Noise Benefits Due to Nacelle Suppression

For engines 1 and 2, full nacelle wall treatment at the inlet and the fan duct reduces the noise at the FAR 36 points by about 7.5 to 8.5 EPNdB. The systems EPNdB levels on a traded basis are:

Engine 1 without advanced technology: 8.6 EPNdB below FAR 36

Engine 2 without advanced technology: 7.9 EPNdB below FAR 36

Engine 2 with advanced technology: 11.7 EPNdB below FAR 36

This is achieved at a relatively small cost as discussed in the following section.

The use of a single splitter at the inlet yields an improvement of about 1.5 EPNdB for both engines 1 and 2, but at a considerable performance penalty. While this permits engine 1 to meet the FAR 36 - 10 EPNdB goal, the payoff relative to loss must be considered as somewhat marginal. A more efficient alternative method toward achieving the same goal should be sought in any future design effort.

Maximum suppression by the use of two inlet and two short aft splitters, in addition to wall treatment, brings about an improvement over wall treatment of only about 4 EPNdB. The systems EPNdB levels on a traded basis are:

Engine 1 without advanced technology: 12.7 EPNdB below FAR 36

Engine 2 without advanced technology: 12.3 EPNdB below FAR 36

Engine 2 with advanced technology: 15.3 EPNdB below FAR 36

The effect of DOC is quite significant, as discussed in the next section. Further advanced technology effort should be given to the control of inlet-radiated noise without the use of inlet splitters.

Jet noise at take-off power is the key limiting factor which prevents engine No. 2 from attaining much below FAR 36 - 15 EPNdB. FAR 36 - 20 EPNdB cannot be reached even with new aircraft operational procedures due to the jet noise floor associated with the current cycle selection. However, by combining a two-position jet nozzle and special operating procedures, engine No. 2 with two inlet and two short aft splitters can approach FAR 36 - 18 EPNdB on a traded basis. A two-segment approach is extremely beneficial in alleviating approach noise.

Economic Penalties of Noise Suppression

The effect of noise suppression treatment was evaluated for the configurations shown on Figures 48 and 49. Wall treatment suppression effects were evaluated separately for both engines, as well as the effects due to the total suppression shown for each case. Inlet and exhaust duct walls are treated to the maximum extent possible, and the associated weight and cost penalties are based on the assumption that the second panels are integrated with the nacelle structure. Incremental weight and cost of the suppression treatment are added to the weight and cost penalties incurred by each engine when scaled back to the same installed cruise thrust to obtain the total weight and cost penalties.

The penalties of noise suppression versus traded noise are presented for a three-engine, Mach 0.98 aircraft in Figure 55 for engine No. 1, without fan source noise reduction or aircraft operational procedures. ATT No. 1 has a noise objective of FAR - 10 EPNdB. This figure shows the relative "efficiency" of treatment, with wall suppression being very effective when fully integrated into the nacelle and engine structure, and the addition of a single inlet splitter being very costly.

The same information is presented in Figure 56 for ATT engine No. 2, which has a noise objective of FAR 36 - 15 EPNdB. Additional fan noise suppression over that shown is required to meet this noise objective when no fan source noise reduction is assumed. The difference in economic penalties with and without fan source noise reduction indicates the desirability of aggressively pursuing aerodynamic developments aimed at reducing fan source noise. It should be noted that, without the benefit of fan source noise reduction, the technology payoff of ATT No. 2 relative to ATT No. 1 shown earlier may be more than offset by the noise suppression penalties as the noise objective is raised from 10 to 15 EPNdB below FAR 36. The decrease in return on investment (ROI) due to noise suppression treatment is shown for both engines in Figure 57.

Water Injection Penalties

It was shown earlier that, in order to meet the oxides of nitrogen emission levels of this study, combustor water injection was required. The estimated penalty of introducing a water injection system into the engine, in terms of aircraft gross weight, is shown in Table XXXVI. Two minutes of operation at take-off power have been assumed. In addition, the effect of compressor inlet water injection to maintain compressor exit temperature (T_3) within design limits at takeoff on hot days is also shown for engine No. 2.

The table indicates that relatively small gross weight penalties are incurred for water injection. It should be noted that, once water injection capability is introduced in the engine, it could be used to augment take-off thrust, if required, since it is quite effective in this regard. At constant turbine inlet temperature, 1% compressor inlet water injection increases thrust approximately 10%, provided that fan aerodynamic and mechanical overspeed capabilities are available.

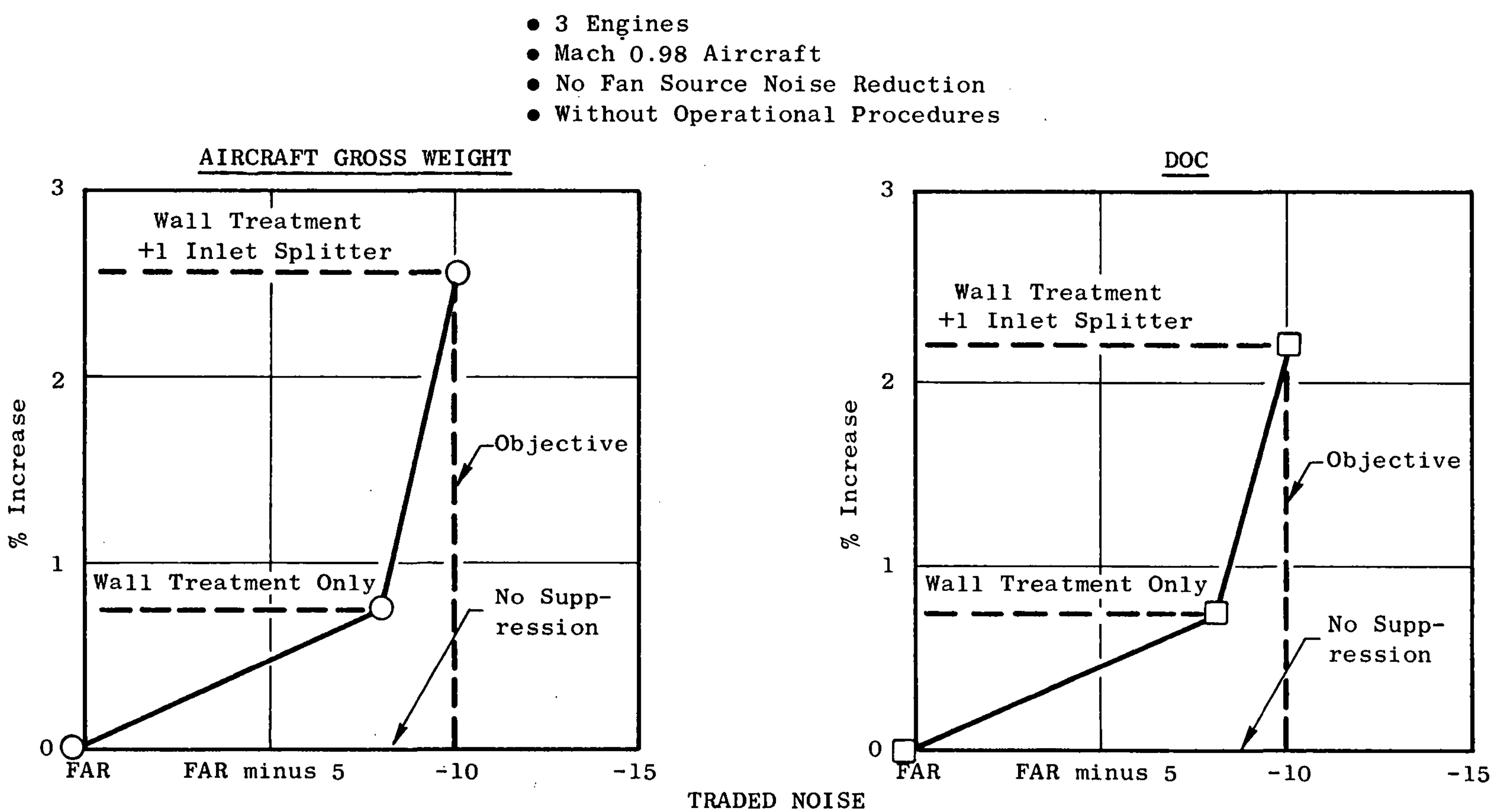


Figure 55. ATT No. 1 Penalty of Noise Suppression.

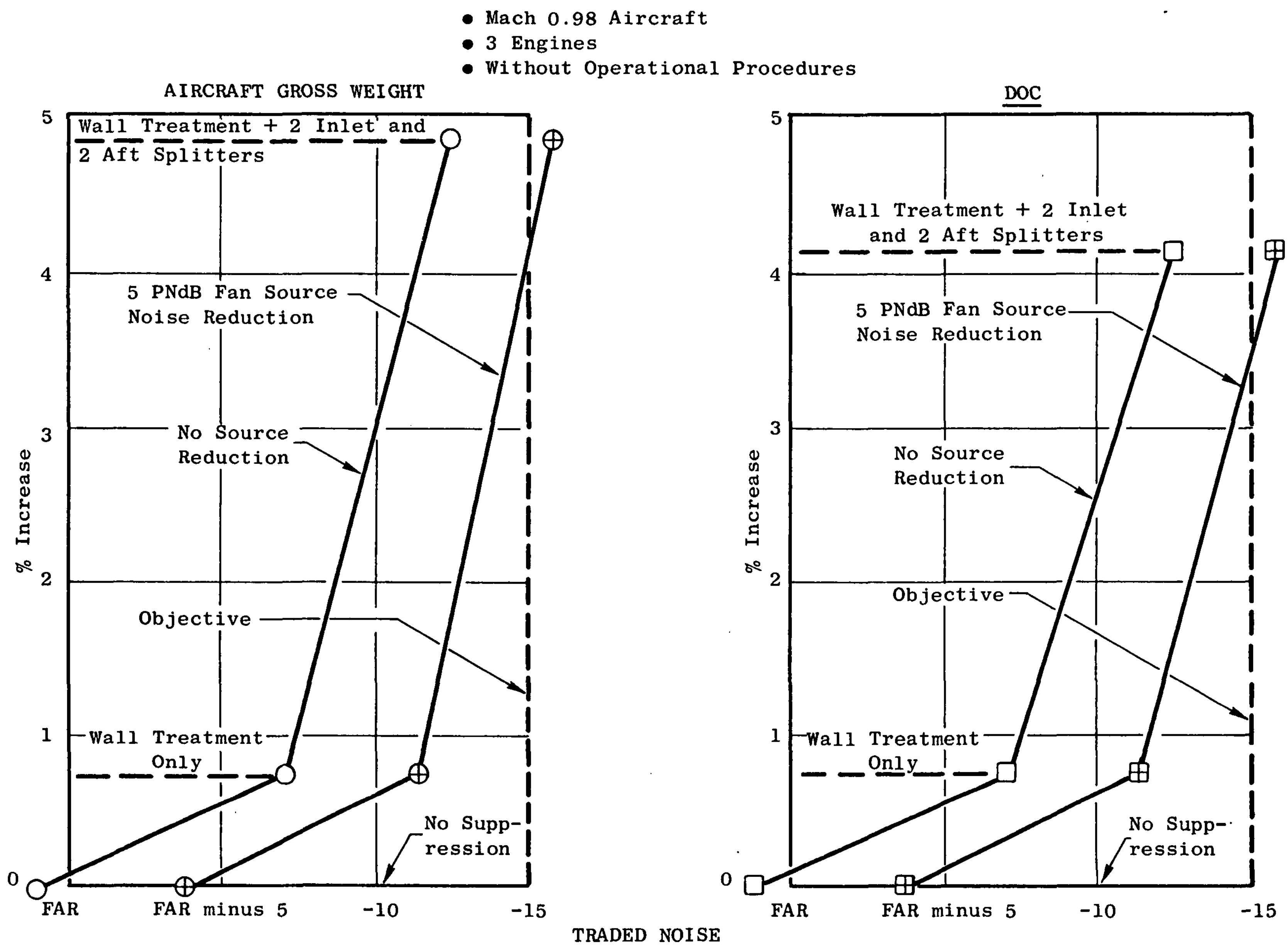
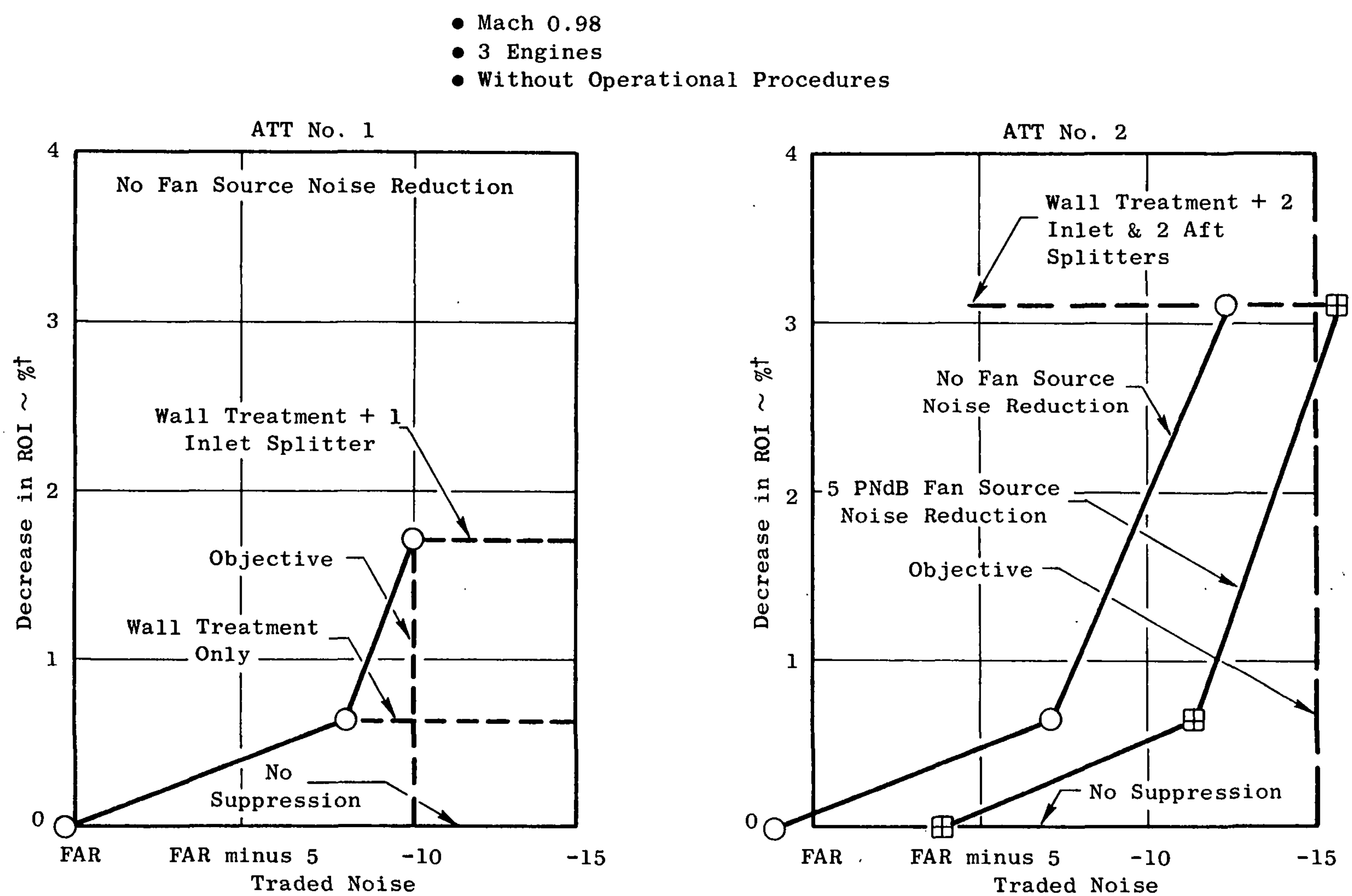


Figure 56. ATT No. 2 Penalty of Noise Suppression.



† % Decrease in ROI (1%) as from 25% to 24%

Figure 57. ROI Penalty of Noise Suppression.

TABLE XXXVI. ESTIMATED WATER INJECTION PENALTIES.

Parameter	ATT No. 1	ATT No. 2
A. Combustor Water Injection NO_x Control		
H_2O Required to Meet Objectives (3 g NO/kg Fuel)	2 to $2\frac{1}{2}$% W_{2C}	$2\frac{1}{2}$ to 3% W_{2C}
H_2O Required/Engine for 2 Minutes at Take-off Power	227 to 272 kg (500 to 600 lbs)	227 to 272 kg (500 to 600 lbs)
B. Compressor Water Injection T_3 Control		
H_2O Required	---	0.6% W_{2C}
H_2O Required/Engine for 2 Minutes at Take-off Power	---	68 kg (150 lbs)
C. Total Water Required/Engine	227 to 272 kg (500 to 600 lbs)	295 to 340 kg (650 to 750 lbs)
D. Weight Penalty of System/Engine		
Control, Pump, Valves, Piping	13.6 kg (30 lbs)	18.1 kg (40 lbs)
Water Tank	11.3 kg (25 lbs)	13.6 kg (30 lbs)
Total System Weight Penalty	24.9 kg (55 lbs)	31.8 kg (70 lbs)
E. Estimated Effect on TOGW	Δ TOGW	
System Weight	+ 0.13%	+ 0.17%
Water, Assumed Expended After 2 Minutes	+ 0.12%	+ 0.15%
Total Penalty	+ 0.25%	+ 0.32%

Payoff of Advanced Technology Engines Vs. Current Technology

A comparison of both ATT engines with an engine that is representative of today's technology is presented in Table XXXVII. The current technology engine is taken from the Task I parametric study and has the same cycle pressure ratio and turbine inlet temperature as the CF6-50, but incorporates a higher pressure ratio fan which is more favorable to the ATT flight condition. The highest single-stage fan pressure ratio that could reasonably be expected in a 1972 engine was estimated to be about 1.75.

This engine then was scaled to the same installed cruise thrust as the ATT study engines and compared in the ATT mission using engine No. 1 as the base. In spite of its lower specific thrust, it has a higher installed because it is a separate-exhaust configuration with increased length and, therefore, more drag. The weight is based on CF6-50 technology which results in a much heavier engine when sized for Mach 0.98 cruise thrust. Compared to the most conservative (in terms of weight) version of ATT No. 2, the differences in aircraft gross weight, DOC, and ROI are dramatic; i.e., 12% 7.9%, and 5.4%, respectively (cost effects are not included in economic factors). Figure 3 provides some perspective of the engine size difference involved between ATT No. 2 and the current technology CF6-50 engine at the same take-off thrust.

TABLE XXXVII. ATT ENGINE PAYOFF VERSUS CURRENT TECHNOLOGY ENGINE.

- M = 0.98 Aircraft
- Cruise Sized Engines

Parameter	Engine Based on Current Technology	ATT No. 1	ATT No. 2
Fan Pressure Ratio	1.75	1.83	1.85
Bypass Ratio	5	4.1	5.6
Turbine Inlet Temperature	1560 K (2350° F)	1645 K (2500° F)	1920 K (3000° F)
Cycle Pressure Ratio	30	30	37
Exhaust Type	Separate	Mixed	Mixed
Specific Thrust, M = 0.98	15	19	19
Δ sfc, Installed	+ 0.5%	Base	- 2.5%
Δ Weight, Installed	+ 1452 kg (+ 3400 lbs)	Base	- 454/- 1180 kg (-1000/-2600 lbs)
Δ TOGW	+ 7.9%	Base	- 4.1%/- 7.6%
Δ DOC†	+ 4.8%	Base	- 3.1%/- 5.2%
Δ ROI†	- 3.3%	Base	+ 2.1%/+ 3.5%

† Not including cost effects

TASK III - IDENTIFICATION OF ADVANCED TECHNOLOGY FEATURES

Advanced technology features have been incorporated into the design of both ATT engines. As a natural result of its later certification date (1985), engine No. 2 is a more advanced engine. The following paragraphs identify, on a component basis, the advanced technology features incorporated and define their potential payoff.

FAN

Advanced technology features for the fan include high pressure ratio (1.8 - 1.9) in a single stage with high tip speed, 503 - 533 m/sec (1650 - 1750 ft/sec) and high specific flow, > 205 kg/sec-m^2 (42 lb/sec-ft^2). Fan source noise reduction features will be incorporated. In ATT engine No. 2, extensive use of composite materials (blades, frame, booster stages, and discs) is anticipated and a "fail-safe" disc design is highly desirable.

Potential Payoff: Reduced weight, noise, cost, and drag. Improved performance and economics with increased safety.

COMPRESSOR

Advanced technology features of the core engine compressor include high pressure ratio (12-14) in a reduced number of stages with casing treatment for stall margin improvement. The ATT No. 2 compressor is designed to obtain 14:1 P/P in 8 stages, compared to the 12:1 P/P in 9 stages for ATT engine No. 1. Composite blading for the front stages of the ATT No. 2 compressor is utilized.

Potential Payoff: Reduced weight and cost.

COMBUSTOR

Advanced technology features to improve combustor performance and life and to reduce emission levels have been incorporated into both ATT combustor designs. ATT No. 1 features a straight step diffuser design, a 3-stage carbureting fuel injection system, and a compressor discharge bleed system to reduce idle emissions. ATT engine No. 2 utilizes a parallel step diffuser design and a double-annular-slot carbureting fuel injection system capable of operating with only one annulus at low power settings to reduce idle emissions. Both combustors have higher space rates than current technology engines, and both are designed for water injection to reduce NO_x emissions at takeoff. The liner cooling concepts also represent advanced technology in that less liner cooling air is required, resulting in better circumferential temperature distribution and, therefore, increased combustor life. ATT No. 2, for example, employs a film-impingement-cooled liner.

Potential Payoff: Reduced emissions and improved performance and life.

TURBINES

High temperature, highly loaded turbine designs incorporating advanced materials and cooling concepts represent advanced technology features of both the high and low pressure turbines for the two ATT engines. The high pressure turbines are both high-pressure-ratio, high-work-extraction, single-stage designs. Turbine inlet temperature (hot day takeoff) for ATT No. 1 is 1645° K (2500° F); ATT No. 2 has a 1920° K (3000° F) T_4. Both temperature levels represent advancements over current commercial engine technology. Other advanced features of the ATT No. 2 high pressure turbine include a redundant disc design, advanced materials, and (possibly) laser-drilled blades with full film cooling as an attractive option to dramatically decrease cost and weight.

The low pressure turbines are likewise air cooled, high temperature, and highly loaded. Compared to current technology turbines, the ATT low pressure turbines utilize fewer stages than would comparable engines with current state-of-the-art loadings, thus reducing weight and overall engine length. The ATT No. 2 low pressure turbine utilizes short-chord blading on the uncooled stages and an inertia-welded rotor. Source noise reduction features for these turbines also are planned.

Potential Payoff: Lower weight and noise; improved performance and safety.

CONTROLS AND ACCESSORIES

An analog control system has been selected for ATT engine No. 1 while electronic digital computation is proposed for ATT engine No. 2. These control systems are capable of being integrated with the aircraft power management system. Both ATT engines incorporate an optical pyrometer - turbine blade temperature limiter as an advanced technology feature to monitor and control turbine blade temperature more precisely, thereby increasing parts life or reducing design temperature margins.

Multifunction accessories (e.g., a combined starter/generator) have also been considered for ATT No. 2.

Potential Payoff: Increased control flexibility, reduced aircraft crew work load, increased parts life, and easier interface between engine system and aircraft power management system.

EXHAUST SYSTEM

For the ATT mission, which requires a high specific thrust engine, the mixed-exhaust concept enables a given level of specific thrust to be obtained at lower values of fan pressure ratio than are required for a separate-flow cycle. This, in turn, leads to the selection of a single-stage fan (rather than a two-stage fan) with resultant advantages in design simplicity, nacelle length, weight, and cost. Additional advantages of the mixed-exhaust system include improved engine performance (∿2% reduction in sfc on an installed basis), higher reverse thrust using only a fan reverser, lower exhaust temperatures, and increased tolerance to cycle unbalance (significant from an engine growth standpoint).

INSTALLATION

From an installation viewpoint, advanced technology aero/acoustic features are significant. A thin-lip inlet with variable geometry features and minimum noise penalties is required. Extensive noise suppression treatment, which has been incorporated into the design of both ATT engines, requires much development for maximum integration with the nacelle and to achieve maximum noise suppression on a cost effective basis.

RECOMMENDED ADVANCED TECHNOLOGY PROGRAMS

Several programs are considered necessary to develop the required advanced technology for an ATT aircraft in the 1985 time period. This section documents, in a priority ranking, such programs specifically applicable to the ATT.

Integrated Fan and Inlet Aero/Acoustic Program

The low noise goals for an advanced technology transport aircraft have made aero/acoustics a key problem. The integrated fan and inlet aero/acoustic program recommended herein addresses this key problem area and has the following objectives:

- Obtain basic aero/acoustic data essential to ATT engine design requirements.
- Determine the effect of various inlet and aft engine suppression configurations on aero/acoustic characteristics.

To accomplish these objectives, the following test vehicle and facilities are required:

- Single-stage fan/inlet test vehicle designed for high pressure ratio, high tip speed, and high specific flow.

- Calibrated acoustic field.

- Facility with adequate capability for measuring aerodynamic performance and with sufficient versatility to accommodate various aerodynamic modifications and hardware changes, to evaluate various acoustic approaches, and to readily incorporate any new measurement techniques such as Laser-Doppler velocimeter, etc.

The scope of the proposed program encompasses the design and construction of a high tip speed, single-stage fan in 36-inch-diameter size, based on the ATT No. 2 fan preliminary design. Initial aerodynamic, mechanical, and acoustic design effort is presently underway. Testing of this vehicle will be conducted to obtain complete aero/acoustic data, including the effects of various inlet and aft end suppression configurations on total system noise. All testing will be conducted at General Electric's remote test facility at Peebles, Ohio, utilizing the scale model fan component test facility currently being used for the NASA Quiet Engine Program half-scale fan acoustic evaluations.

The technical approach to this proposed program consists of three distinct phases:

- Aero/acoustic performance determination

- Fan source noise reduction effort

- System suppression evaluation, including acoustic treatment and high Mach throat inlet effects

The aero/acoustic performance determination phase will consist of testing to establish the aerodynamic performance of the scale model fan and measurement of its baseline acoustic levels.

An extensive fan source noise reduction phase is recommended and will consist of testing to evaluate several blade designs to determine the effect of blade design changes on fan source noise levels. Then, using the best blade design, acoustic tests at various rotor/outlet-guide-vane spacings are proposed to determine the effect of spacing on fan source noise for a high tip speed design. Returning to the original rotor-OGV spacing and retaining the best blade design, additional acoustic tests with leaned outlet guide vanes are recommended. Again, returning to the standard OGV orientation, a final test series is recommended to determine the effect of various numbers of outlet guide vanes on fan source noise levels.

The system suppression evaluation phase of testing will concentrate on inlet systems and aft end systems suppression. Inlet systems testing will be conducted with a contoured inlet and varying numbers of treated inlet splitters. Choked inlet concepts utilizing either a mechanical throat or translating splitters will be evaluated. The effect of one and two treated splitters in the aft fan duct will be evaluated during the aft end systems testing.

A schematic of the recommended aero/acoustic test vehicle is presented in Figure 58. This vehicle with a contoured inlet, two inlet splitters, and two aft splitters, appears as Figure 59.

The ATT study has shown that fan aero/acoustic considerations represent the most critical barrier to the successful development of an ATT propulsion system. The single-stage, high pressure ratio, high tip speed, high specific flow fan design recommended for the ATT application represents technology levels beyond our current knowledge. Since no reliable test data presently exist to verify this advanced design, General Electric considers it imperative to initiate this recommended fan and inlet aero/acoustic program.

This recommended program is estimated to require 24 months of technical effort in several distinct phases. The initial phase is the aerodynamic and mechanical design of the fan and inlet. This phase will be followed by hardware procurement and vehicle assembly phases. Once the test vehicle is assembled, it will be shipped to the General Electric scale model fan test facility at Peebles, Ohio, and the important test phase will be initiated. The data analysis, evaluation, and reporting phases will follow the testing.

Successful development of aero/acoustic technology for this advanced single-stage fan design is, in General Electric's judgement, the key to the most promising ATT propulsion system. Initiation of this critical program by the third quarter of 1972 is strongly recommended.

Installation Aerodynamics Investigation

ATT systems studies have shown the desirability of wing-mounted engine arrangements for the larger sizes of advanced transport aircraft. With this arrangement, however, there is the possibility of increased interference drag which, through judicious nacelle positioning and area ruling, can be reduced, eliminated, or, perhaps, even be made favorable. The objective of this proposed program is to define, by wind-tunnel test and methods analyses, the most favorable installation configuration for an ATT aircraft.

The method of accomplishment of this objective is to design and build a scale model engine nacelle; install it on a scale model of a practical, near sonic aircraft configuration; and, via wind-tunnel testing, evaluate a matrix of nacelle positions to determine the most favorable installation configuration for the transport. The matrix of nacelle positions will be determined from engine cycle analysis, aircraft structural analyses, and channel flow theory.

Two specific program phases are envisioned. The first, as described above, would utilize a flow-through nacelle installed on a scale model ATT aircraft. The second phase would integrate the results of the initial testing into the design and construction of powered simulator nacelle models. These

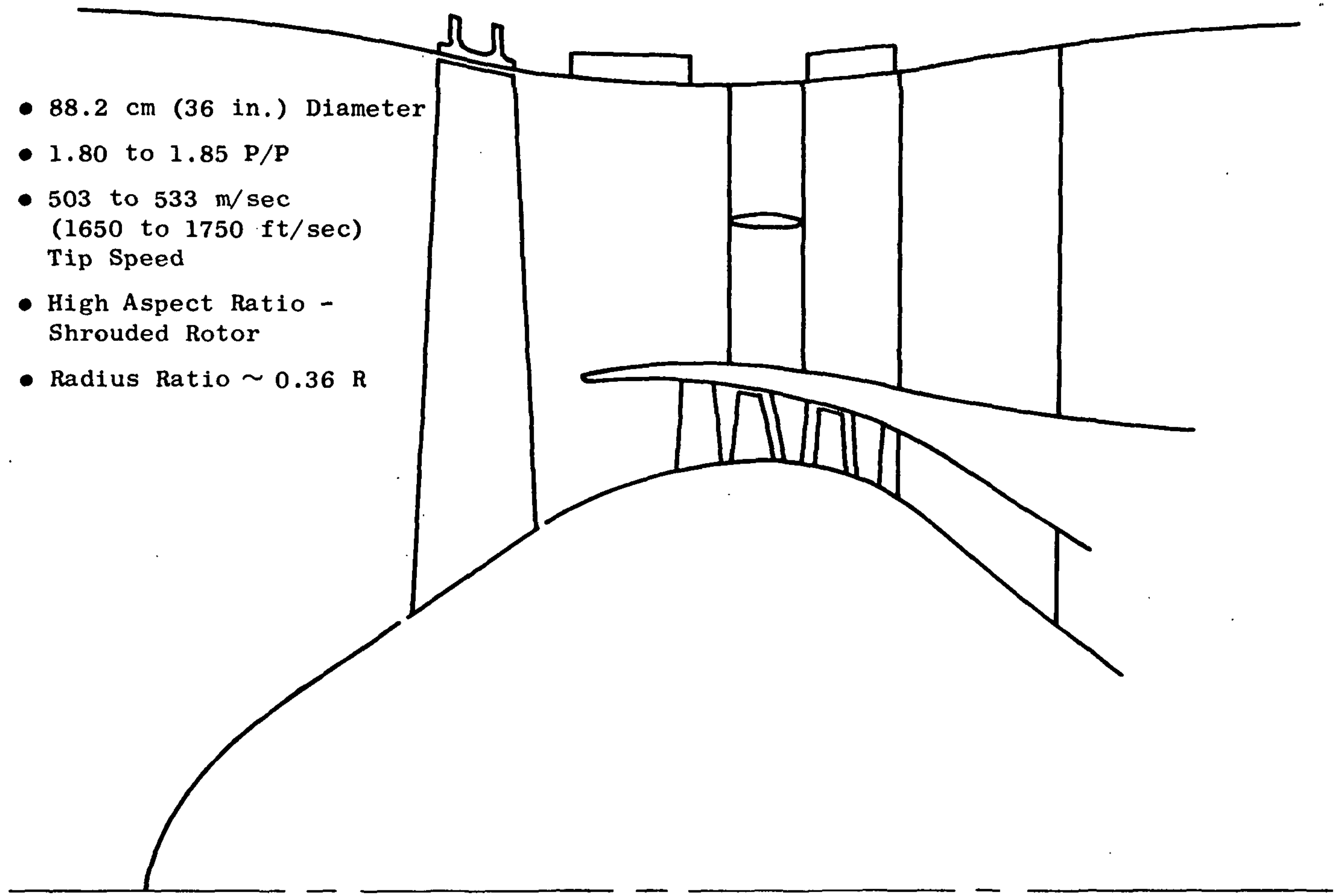


Figure 58. Aero/Acoustic Test Vehicle Schematic.

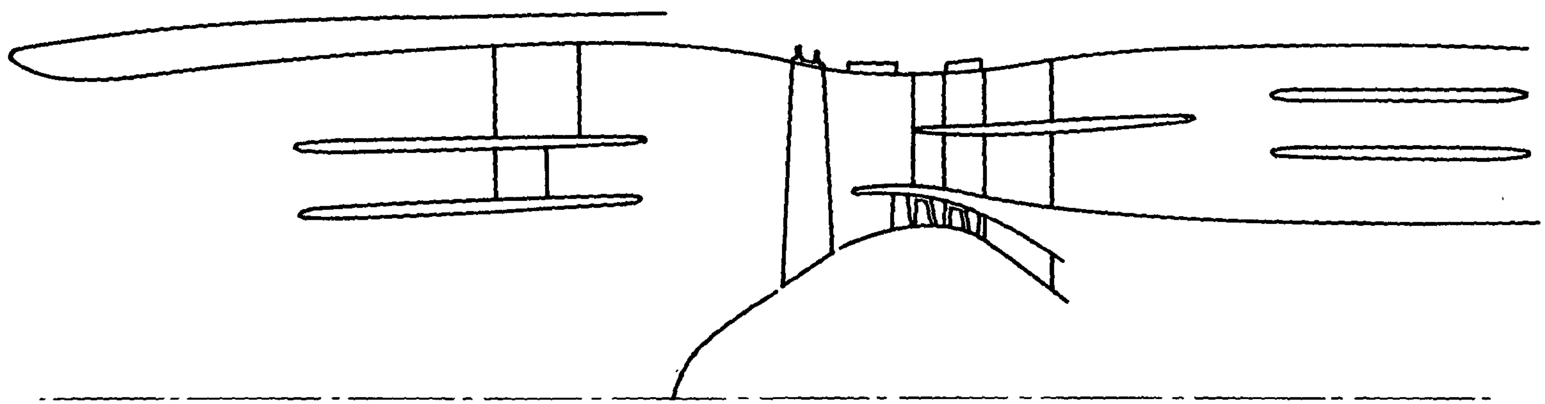


Figure 59. Aero/Acoustic Test Vehicle Schematic with Noise Suppression Treatment.

powered nacelles then would be tested both as isolated nacelles and on a semi-span wing to obtain the necessary data to incorporate the results of power effect into the ATT installation requirements.

The initial phase of this technology program is estimated to require ten months of technical effort as well as support from NASA and the ATT aircraft contractors. Preliminary efforts to initiate such a joint effort presently are underway.

Aerodynamic Investigation of Fan/Core Mixers

General Electric ATT propulsion system studies have shown significant advantages to a mixed exhaust flow cycle. These advantages include improved engine performance, higher reverse thrust capability using only a fan reverser, and lower exhaust gas temperatures. Furthermore, compared to a separated flow cycle, mixed flow provides a given specific thrust level at a lower fan pressure ratio, thus permitting the use of a single-stage fan for the high specific thrust design. The advantages of the single-stage fan have been discussed previously.

The benefits of the mixed flow cycle, however, are predicated on the development of efficient, low pressure loss aerodynamic mixer designs applicable to the high bypass ratio ATT turbofan engines. General Electric has previously developed various partial mixers, one of which is incorporated into the design of ATT engine No. 1. The objective of this proposed program is to establish low loss aerodynamic mixer designs which have the potential of lower weight than chute mixers and are compatible with high bypass ratio ATT engines.

The scope of the proposed program includes the aerodynamic design and evaluation of these candidate mixer systems to assess the most promising concepts and configurations. Once this determination has been made, selected concepts will be designed, built, and tested in a dual temperature flow static thrust facility to establish the performance levels of the mixer and to verify and develop applicable design criteria.

This program, which is specifically applicable to an ATT application, is estimated to require one year of technical effort and, when successfully completed, will yield the necessary technology to provide lower cost, lower weight, less complex (but with comparable performance) mixers for advanced transport application.

Additional Cycle Studies

The results of the current study have indicated that certain engine variable geometry features may hold the promise of achieving significant reductions in noise or emissions with less penalty than achievable by other methods. Consequently, additional study of such features is appropriate.

Such studies were requested in NASA-Lewis REP 3-504336-Q, dated March 15, 1972. General Electric responded with Proposal P72-59, dated March 29, 1972. This proposal contained a detailed discussion of those variable geometry features that may be advantageous for an ATT application and described the technical approach for their investigation. In general, the features proposed for further study include variable geometry, low noise inlet and fan systems, and variable exhaust nozzles.

The duration of the proposed program is six months, and its successful completion will result in the identification of those variable geometry features which may significantly improve the environmental impact of the ATT propulsion system. This program has been initiated under an extension of the original ATT study contract.

Control System Studies

Since steeper glide slopes represent one means of reducing the community noise footprint, it is prudent to investigate various methods of achieving rapid engine thrust response for compatibility with possible new aircraft requirements when this steep approach is used. This potential problem was also addressed in NASA-Lewis RFP 3-504336-Q, and General Electric's proposed program for its investigation was described in Proposal P72-59.

Briefly, the dynamic operating characteristics of ATT engine No. 2 will be modeled, and this dynamic model will be utilized to evaluate various engine acceleration schemes. The effect of these schemes on engine operating characteristics (stall margin, transient temperature capability, overspeed, etc.) also will be evaluated. Finally, for each acceleration scheme selected for evaluation, an assessment of incremental cost, weight, and performance relative to the basic ATT No. 2 design will be made where possible.

This program also is proceeding as an extension of the original ATT study contract.

Other Related Programs

Additional advanced features which benefit other propulsion systems as well as ATT systems are expected to be pursued under other programs. These include:

- High temperature, low-emission combustors
- High temperature turbines
- High temperature materials
- Composite materials
- Fail safe "nonburst" fan and turbine discs
- Tip-shrouded composite fan blades

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Noise*

- Noise levels of 10 EPNdB below FAR 36 will require the successful development of a low noise fan and inlet system in order to limit the economic penalty to our objective level (1% DOC magnitude).

- Noise levels of 15 EPNdB below FAR 36 require additional suppression (multiple splitters) with a substantial economic penalty unless a large improvement in noise technology can be made. Furthermore, noise levels lower than FAR 36 - 15 EPNdB will require flight procedure changes (in addition to power cutback assumed above). Sideline noise becomes limiting (for a three-engine aircraft), and a cycle change would be required to lower the jet noise floor with an appreciable economic penalty to the near-sonic aircraft.

Emissions

- Idle emissions objectives established for the study can be achieved by a feature such as compressor discharge bleed. More advanced combustor concepts have the promise of exceeding these objectives. Smoke does not represent a limiting problem except as it must be developed into the combustor together with other characteristics.

- Although advanced carbureting combustor approaches have the promise of achieving lower NO_x emissions than current combustors without the use of water, the ATT study NO_x emissions objective cannot be met at take-off power except by the use of water.

- Water injection can be incorporated into the engine and aircraft with an order to magnitude less penalty than would be associated with employing a low temperature, low pressure ratio cycle for NO_x emissions reduction. There are also opportunities to minimize the penalty of using water by designing the engine for take-off thrust augmentation.

Engine Cycle and Configuration

- For noise levels in the range of 10 EPNdB below FAR 36, the highest specific thrust engine with a single-stage fan of 1.8 - 1.9 pressure ratio yields the best economics for a Mach 0.95 - 0.98 aircraft. The same cycle is acceptable for a Mach 0.90 aircraft.

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* Based on Mach 0.98; 5556 Km (3000 nautical mile) range; 18,140 Kg (40,000 lb) payload Tri-Jet.

- A single-stage fan engine is shown by General Electric to be superior to a two-stage fan from both economic and noise standpoints.

- A mixed-flow engine and installation design is shown by General Electric studies to be superior to a separate-flow design. The final selection may be dependent upon interference drag evaluation of each aircraft installation.

- High turbine inlet temperature [1920° K (3000° F)] and high overall pressure ratio cycles (35 - 40) offer significant economic advantages based on advanced cooling and materials technology.

Advanced Technology

- Improvement in engine technology to balance the economic penalties of lower noise and emission requirements is difficult and will take extensive effort over a long period of time.

- The most important technology features include the following:

  - High pressure ratio (1.8 - 1.9) fan with high speed [503 - 533m/sec (1650 - 1750 ft/sec)].

  - Inlet features to reduce inlet transmitted noise, particularly MPT noise. Combined system development of fan and high Mach inlet with variable lip features is recommended.

  - Tip-shrouded, lightweight fan blades.

  - Composite fan and low pressure blading and static parts.

  - Double-annular or possibly a variable geometry combustor for idle emissions.

  - Advanced combustor for reduced NO_x emissions. The additional use of water for the very low ATT study NO_x objectives, combined with an engine designed to take advantage of water.

  - Redundant or other "nonburst" fan and core turbine disc approaches.

- Follow-on preliminary design studies should be conducted to further identify the payoff of different features and to guide component research work involved with this category of engine.

- Improved flight safety also should be a focal point of advanced engine technology work, the disc burst problem being the most important.

RECOMMENDATIONS

- Since General Electric does not believe that a new long range, higher Mach aircraft will be developed for the late 1970's (because of airline needs and airline and aircraft industry financial capability), NASA should point toward advanced engine technology for the 1980's with the objective of improving aircraft economics and speed to provide the necessary incentive for new aircraft development.

- From the engine standpoint, a noise level of 10 EPNdB below FAR 36 with minimum economic penalty is recommended as the goal for this new high speed transport.

- NASA should sponsor an integrated fan and inlet aero/acoustic program to supply the fan technology required for this high speed transport.

- The following emissions goals for advanced engines are recommended:

Idle:	H/C - 4 g/kg fuel
	CO - 30 g/kg fuel
Takeoff:	NO_2 - 25 g/kg fuel without water
	NO_2 - 10 g/kg fuel with water
	Smoke - nonvisible

APPENDIX - SYMBOLS

Symbol	Definition	Units
A	Area	meter^2 (in.^{2})
ATT	Advanced Transport Technology	---
C-D	Convergent-Divergent Nozzle	---
CDP	Compressor Discharge Pressure	N/m^2 (lb/in.^{2})
dB	Decibel, re: 0.0002 dynes/cm^2	---
D	Diameter	meter (in.)
DOC	Direct Operating Cost	---
EPNL	Effective Perceived Noise Level	EPNdB
F	Thrust	newton (lb)
FAR	Federal Aviation Regulation	---
g	Acceleration Due to Gravity	9.8067 m/sec^2 (32.174 ft/sec^2)
h	Specific Enthalpy	J/kg (Btu/lb$_m$)
HP or hp	Horsepower	watt (hp)
IGV	Inlet Guide Vane	---
J	Mechanical Equivalent of Heat	(778.16 ft-lb/Btu)
L	Length	meter (in.)
$(L/D)_{eq}$	Equivalent nacelle fineness ratio (See Figure 42)	---
M	Mach Number	---
MDOF	Multiple Degree of Freedom	---
MPT	Multiple Pure Tones	---
N	Rotational Speed	rad/sec (rpm)
P	Total or Stagnation Pressure	newton per square meter (lb/in.^{2})
PNL	Perceived Noise Level	PNdB
ROI	Return on Investment	%
SDOF	Single Degree of Freedom	---
sfc	Specific Fuel Consumption	kg/kg$_f$-hr (lbm/lb-hr)
T	Total or Stagnation Temperature	° K (° R) (° F)
TOGW	Aircraft Take-off Gross Weight	kg (lbm)

Symbol	Definition	Units
U	Rotor Speed	m/sec (ft/sec)
$U/\sqrt{\theta}$	Corrected Rotor Speed	m/sec (ft/sec)
V	Velocity	m/sec (ft/sec)
W	Weight Flow	kg/sec (lbm/sec)
$W\sqrt{\theta}/\delta$	Corrected Weight Flow	kg/sec (lbm/sec)
α, β	Angles	radians (degrees)
β	Bypass Ratio = $\frac{\text{Bypass Flow}}{\text{Core Flow}}$	---
δ	Pressure Correction, $\left(\frac{P}{1.01325 \times 10^5}\right)\left(\frac{P}{N/m^2 \; 14.696 \; lb/in.^2}\right)$	
Δ	Difference	---
η	Efficiency	---
θ	Temperature Correction, $\frac{T}{288° \; K}$ $\left(\frac{T}{518.67° \; R}\right)$	---

Subscripts

I,i	Installed	---
f	Force, Fuel	---
m	Mass	---
s	Static	---
T, t	Tip	---
0	Free Stream	---
1	Low Pressure Rotor	---
2	High Pressure Rotor, Fan Face Inlet Station	---
2c	High Pressure Compressor Inlet Station	---
3	Compressor Discharge Station	---
4	High Pressure Turbine First Rotor Inlet Station	---
8	Nozzle Throat Station (mixed or primary)	---
28	Bypass Flow Nozzle Throat Station (separate exhaust)	---
9	Core Nozzle Exit (complete expansion)	---
29	Bypass Flow Nozzle Exit (complete expansion)	---

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